ENERGY IN IRRIGATION
IN
DEVELOPING COUNTRIES

An Analysis of Energy Factors
to be
Included in a National Food Policy

by

Ernest T. Smerdon, P.E.
and
Edward A. Hiler, P.E.

Prepared for the Agency for International Development
Project No. 930-0091

December 1980

ENERGY EQUIVALENTS1/

	Kcal2/	MJ	Kwh	Hp-hr	Btu	bbl oil3/	metric ton coal4/
Kcal	1	4.19×10^{-3}	1.16×10^{-3}	1.56×10^{-3}	3.97	7.0×10^{-7}	1.4×10^{-7}
MJ	238.8	1	0.2778	0.3725	947.8	1.7×10^{-4}	3.4×10^{-5}
Kwh	860	3.60	1	1.341	3412	6.0×10^{-4}	1.2×10^{-4}
Hp-hr	641.2	2.685	0.7457	1	2545	4.5×10^{-4}	9.1×10^{-5}
Btu	0.252	1.06×10^{-3}	2.93×10^{-4}	3.93×10^{-4}	1	1.8×10^{-7}	3.5×10^{-8}
bbl oil	1.4×10^{6}	6.0×10^{3}	1.7×10^{3}	2.2×10^{3}	5.7×10^{6}	1	0.203
metric ton coal	7.2×10^{6}	3.0×10^{4}	8.4×10^{3}	1.1×10^{4}	2.9×10^{7}	4.93	1

1/ To convert from unit in the left column to units in other column headings, multiply known quantity by factor in table. For example, how many MJ's (megaJoules) are equivalent to 12,000 Btu's? Answer: 12,000 Btu x 1.06 x 10^{-3} MJ/Btu = 12.72 MJ. Terms used are: Kcal = Kilocalorie, MJ = megaJoules, Kwh = Kilowatt-hour, Hp-hr = horsepower-hour, Btu = British thermal units, bbl oil = energy equivalent of one barrel of crude oil, and metric ton coal = energy equivalent of one metric ton of coal (100 kilograms).

2/ 1 Kcal (large calorie or kilogram calorie) = 1000 cal (small calorie or gram calorie)

3/ Approximate conversion only which varies with source of crude. 1 bbl = 42 gallons = 159 liters

4/ Approximate conversion only which varies with source of coal.

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EXECUTIVE SUMMARY

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Irrigation in developing nations in 1972-73 consumed energy at an annual rate of 24,300,000,000,000 kilocalories per year. Included in this is only the energy to manufacture the pumps, engines, pipes and other components of the irrigation system and operate the system. The energy required to develop the water supplies for the irrigation, such as constructing reservoirs and drilling wells, is not included. By 1985-86 this energy use is projected to have increased to an annual rate of 38,600,000,000,000 kilocalories per year -- an increase of 53 percent in this 13 year period.

This report assesses the energy use in irrigation in developing countries for the purpose of determining the best means to reduce the magnitude of this growing and costly energy demand. The potential for technological solutions to the problem of increasing demand for energy for irrigation is reviewed and critically analyzed. The following summarizes the findings which we hope will be useful to those faced with policy decisions regarding energy for irrigation in developing countries.

No data are available on the energy that is required to develop water supplies for irrigation from either surface water resources or the groundwater. Calculations to determine this are made in the report and they show that, in general, the annual energy cost to develop reservoirs and associated canal works for surface supplies is about 178,000 Kcal/year for each hectare provided with irrigation water. The annual energy cost per hectare to provide tubewell supplies is over twice as much, being about 410,500 Kcal/yr. Therefore, all factors considered, it takes less than half as much energy to provide irrigation supplies from surface sources. However, surface supplies often are not available.

The energy required to manufacture irrigation system components and install the irrigation systems on the farms also was determined. Included were surface irrigation systems with and without irrigation runoff recovery systems, a hand-moved sprinkler system and a trickle system. Similarly, the energy required to operate each of the systems was determined. In each case, the surface irrigation system is the most energy efficient to manufacture, install and operate under conditions typical of irrigation in most developing countries. Only when pumping lifts are very great, approaching 100 meters (well in excess of that generally found in LDCs), are the sprinkler and trickle systems competitive on an energy use basis. And then the high cost of sprinkler or trickle systems precludes their widespread use in developing countries. The importance of pumping energy is illustrated by the fact that for surface irrigation supplied by groundwater, over 96 percent of the total energy required is for pumping when the pumping lifts are 50 meters or more. Even when pumping lifts are less the energy for pumping predominates.

The potential energy savings possible with improvements in watercourses and on-farm irrigation systems, such as with precision land leveling and installation of underground pipe, is analyzed. Case studies are presented to show the amount of energy that may be saved with these measures, which can markedly reduce the water losses in the system. A procedure for calculating the energy savings possible is given. Using field data from the case studies, it is shown that energy savings through improvements in watercourses and the irrigation system on the farm can amount to 50 percent or more.

The alternate renewable energy technologies which may have potential in irrigation systems in developing countries are discussed. The various possible alternate energy sources from agricultural biomass materials, including wastes, as well as the possible increased use of solar energy and wind energy are analyzed. Biomass systems considered include direct combustion, gasification, pyrolysis of plant residues, methane production by anaerobic digestion of animal wastes, ethyl alcohol (ethanol) production from starchy and sugary crops, and production of a diesel fuel substitute from plant oils. The desirability and potential problems with each biomass fuel source are discussed. The use of agriculturally produced biomass materials for fuel instead of food poses a problem because of short supplies and the ever-present food/fuel conflict occurring in the food deficient nations.

The potential for various direct uses of solar power including photovoltaic cells, shallow solar ponds collecting energy to drive Rankine cycle engines and other collectors to provide energy to drive pumps are also discussed. Moreover, wind power is reviewed as an alternate energy source and its potential is assessed. Such issues as costs, the dependability and risk factors involved with each technology, and the state of the technology and its suitability for developing countries are analyzed. Rankings in terms of the likelihood that the technology will be suitable for developing countries, considering cost, show wind energy to be highest, followed by biomass energy sources, then solar energy. The position of solar energy could greatly improve if some of the speculated breakthroughs occur, but capital cost will remain very high even if the most optimistic progress is made.

The individual options for irrigation energy alternatives are assessed in terms of the impact of each on the food production effectiveness of irrigation systems. Here the importance of timing of irrigation and having an energy supply that is capable of providing irrigation water at the specific time of critical crop water demand is stressed. This is a critical issue for several of the systems such as windmills, which are totally dependant upon the availability of adequate wind supplies. The sensitivity of alternate energy systems to operational problems is also considered.

The greatest potential for saving energy is shown to result from the elimination of water losses. Ideally, every drop of water should go to the plant root zone so it can be used by the crops. Preventing losses in canals and those from over-irrigating fields because of poorly designed or operated systems saves both water and energy and should be a high priority consideration.

Specific recommendations for saving energy and water through research and development are provided. The general order of priority is: (a) reduce water losses in the watercourse and water distribution system; (b) improve on-farm irrigation practices such as by precision land leveling; (c) be sure irrigation pumps are operating as efficiently as possible and are in good repair; (d) make sure the crop water needs are known and crops are not irrigated in excess of their needs; and (e) use surface water when available to achieve the lower energy cost of surface water supplies. Research and development should concentrate on helping accomplish the best water management possible on the farm. Research on sophisticated and technologically complex alternate energy sources will continue in the industrialized, developed nations and the breakthroughs which have potential for LDC application should be adapted to developing country conditions through appropriate developmental activities.

Finally, it is very important for all governments to realistically assess the energy commitments required if their nation's irrigation systems are to produce needed food. All options can then be analyzed and the impact of each on energy balance and economic strength of the nation can then be determined. This is an important national policy consideration.

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Chapter I

INTRODUCTION

World Energy Resources

To place in perspective the importance of energy supply and cost on the future of irrigation in developing countries, a brief look at the world energy picture in is order. Some energy sources, such as energy from biological production, hydroelectric power, wind and direct solar radiation, come directly or indirectly from the sun and are renewable. Other energy supplies originate from solar or geologic sources and constitute stored, non-renewable energy sources. These include fossil energy such as coal and petroleum products and nuclear energy. In developing countries human and animal physical energy is important and is renewable. The supply of energy from fossil fuels is finite and demand will continue to drive prices higher and higher. Currently, one of the most convenient and widely used fuels for irrigation applications is oil or gas for internal combustion engines. The future oil and gas supply situation is particularly critical. Electricity, although not a primary energy source, is an equally convenient power source and is usually generated by burning fossil fuels, but may come from hydroelectric or nuclear plants.

Estimates of ultimately recoverable world energy reserves are highly speculative. What is not speculation is the fact that world energy demand rate in recent decades has grown at a faster rate than the world population, see Figure 1 (33)*. Also, it is known that per capita energy consumption in developed countries is much higher than in developing countries, see solid lines in Figure 2. The World Bank recently reported a projection which shows a future growth rate in energy consumption to be higher in the developing countries than in the developed countries, see Table 1 (12). However, the per capita energy consumption rate for developed countries will continue to far out-distance the developing countries for many years to come.

Table 1. World Commercial Energy Consumption, 1975-90
(Million barrels a day of oil equivalent)

	1975	1980	1985	1990	Average Annual Growth, Percent 1950-74	1975-80	1980-90
World	122.1	137.8	166.0	201.5	5.0	2.5	3.9
Developed Countries	108.2	121.1	143.7	170.9		2.3	3.5
Developing Countries	13.9	16.7	22.3	30.[illegible]	6.9	3.7	6.2
Oil Importing Developing Countries	10.4	12.4	16.8	22.8	6.9	3.6	6.3
Oil Exporting Developing Countries	3.5	4.3	5.5	7.8		4.2	6.1

SOURCE: Adapted from Energy in the Developing Countries, World Bank, August 1980.

*Numbers in parentheses refer to the references appended to this report.

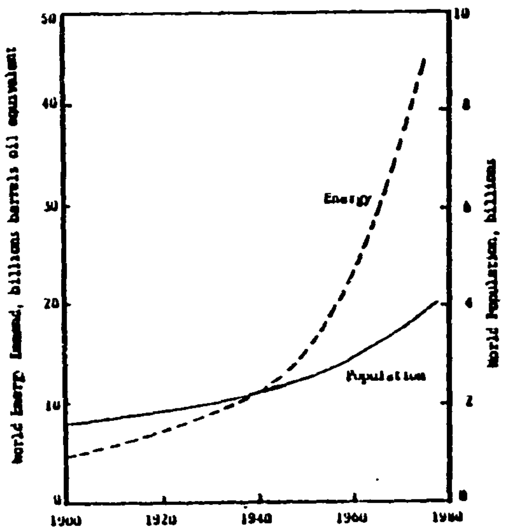

Figure 1. World Energy Demand and World Population

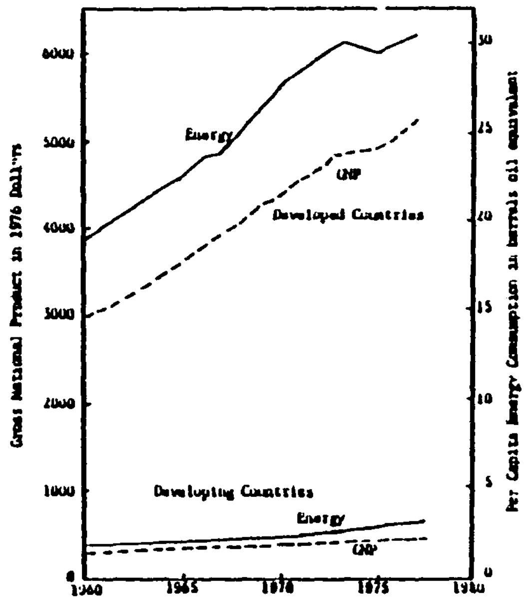

Figure 2. Per Capita Energy Consumption and Gross National Product

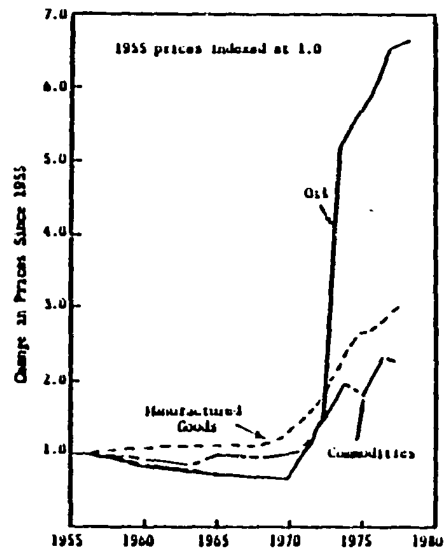

Figure 3. Changes in Export Price of Oil, Price of Commodities, and Price of Manufactured Goods since 1955.

Historically, the economic and industrial development of countries have closely paralleled energy consumption. While there are variations between individual countries, the overall relation between energy consumption and gross national product is remarkable for both developed countries and developing countries, see Figure 2.

Energy Prices

The last decade has shown the export price of oil to increase by a factor more than six. Commodity prices doubled and the price of manufactured goods more than doubled, see Figure 3. Projections of energy demand have been made based on any of several selected scenarios of the future. For example, the Conservation Commission of the World Energy Conference, based on the work of experts from 76 countries, made several projections of potential world energy demand into the next century (10). The lower projection of the Commission shows world energy demand in 2020 to be 2.5 times the current demand. This represents an average 3 percent annual growth rate for the next forty years, down from that reported for the next ten years in the recent World Bank report, Energy in the Developing Countries (12). Even this lowest of the possible future demands projected by the Conservation Commission shows that energy supplies will be strained and, as a result, the prices for energy cannot be expected to decrease.

Developing countries currently use a small portion of the world's commercial energy -- about 12 percent. By 1990 that percentage will increase slightly to 15 percent, still a small share. The oil importing developing countries will have to import more oil in 1990 than in 1980 because their energy production increase over the decade will not compensate for the consumption increase. The difference between consumption and production must be met by imports, which in 1990 will be 7.6 million barrels a day of oil equivalent versus 4.6 today,1/ mostly in the form of imported oil, see Table 2.

Table 2. Oil Importing Developing Countries: Primary Commercial Energy Balances, 1980 and 1990 (Millions barrels a day of oil equivalent)

Energy	1980 Production	1980 Consumption	1990 Production	(Annual Percent Change) 1980-90	1990 Consumption	(Annual Percent Change) 1980-90
Oil	2.0	6.5	3.6 1/	(6.0%)	11.4	(5.8%)
Gas	1.5	1.4	2.6	(5.6%)	2.6	(6.4%)
Coal	2.4	2.5	3.3	(3.2%)	3.4	(3.1%)
Hydro	1.5	1.5	3.2	(7.8%)	3.2	(7.8%)
Nuclear	0.1	0.1	1.0	(25.9%)	1.0	(25.9%)
Other 2/	0.3	0.4	1.5	(17.5%)	1.2	(11.6%)
Total	7.8	12.4	15.2	(6.9%)	22.8	(6.3%)

1/ With enhanced recovery this figure could increase to 4.8, but 3.6 is more probable.
2/ Includes alcohol, other non-conventional primary energy sources, unallocated energy and exports of gas.
SOURCE: Adapted from Energy in the Developing Countries, World Bank, August, 1980.

1/ A barrel of oil equivalent is the calorific heat content of a barrel of oil. See Table of Energy Equivalents inside the front cover for conversion to other energy units.

Agricultural Energy Use

Agricultural production accounts for a very small portion of the commerical energy used in any nation. Typically, the figure is less than 5 percent of the commercial energy budget of the nation and this low percentage generally applies for both developing countries and developed nations. A major issue facing the developing countries will be that of assuring the energy supply necessary for inputs, such as fertilizer and water for irrigation, essential to an increasingly productive agriculture. The recent World Bank report, Energy in the Developing Countries, states, "There is no readily identifiable yield-increasing technology other than the improved seed-water-fertilizer approach that has characterized the Green Revolution of recent years." Therefore, the energy requirements of this improved technology must have the attention of the government leaders in developing countries.

World Irrigation

The world contains roughly 13,401 million hectares[2/] of land surface with crops occupying about 1,439 million hectares, or about 11 percent of the land area (34). Of the cropped land, about 40 percent is in humid regions, about 40 percent in subhumid regions, roughly 15 percent in semi-arid regions, and only 5 percent in arid regions. The irrigated lands of the world exceed 200 million hectares. This amounts to approximately 15 percent of the cropland of the world. There are over 500 million additional hectares of potentially irrigable land in the world if water can be provided (34). If that additional land is needed for irrigation to feed a hungry world, a critical question is whether it might be prevented because of either energy shortages or excessive costs of energy for irrigation. A summary table showing the extent of irrigation in each country of the world is provided in Appendix I.

In 1972-73 the use of commercial energy for irrigation in developing countries[3/] amounted to 24.8×10^{12} Kcal/yr and by 1985-86, that use is projected to have increased by 55 percent to 38.6×10^{12} Kcal/yr (7). These energy cost calculations include the energy to manufacture pumps, engines, pipes and other irrigation materials and operate them. The energy required to construct and maintain reservoirs is not included. This projected energy use in irrigation is a small portion of the total energy required for agricultural production in developing countries (7.8 percent in 1972-73 and 4.4 percent in 1985-86), but still is equivalent to 27 million barrels of oil. About 84 percent of the energy requirement is for pumping and other operational costs, not in the equipment manufactured.

In extremely arid areas irrigation makes the difference between having a crop and no production whatsoever. In temperate semiarid regions and even subhumid regions, irrigation can provide that soil moisture control so essential if the potential high yields possible with the improved seed-water-fertilizer approach consistently are to be achieved. The

2/ One hectare = 10,000 square meters = 2.47 acres

3/ Included are Africa, Latin America, Far East, Near East and the Asian Centrally Planned Economies (7).

water supply must be dependable and the necessary energy to support the irrigation must also be available and within economic reach of the farmers.

If water is not present in the soil to support crop production, high yields cannot be achieved. Water, either through adequate natural rainfall or irrigation, then is an essential resource. Although on a global basis irrigated cropland constitutes only 15 percent of the cultivated land, this irrigated land produces 30 percent of the world's food. As will be shown later, irrigation requires energy in varying quantities, so energy also is an essential resource for irrigated food production.

Definitions and Energy Units Used

It is important to define which energy terms are used in this report to avoid possible confusion. One term used throughout this report deserves definition and elaboration here. Commercial energy is an energy form that is normally sold in the course of commerce. This includes coal, lignite, charcoal, peat, all petroleum products (oil, gasoline, diesel, kerosene, natural gas and liquified petroleum gas), methane gas, alcohol, and electricity generated with any fuel including nuclear or from hydro sources. Simply stated, commercial energy is that energy for which a direct monetary outlay is required for its use. The term, commercial energy, is virtually synonymous with the often used terms, conventional energy or cultural energy.

Commercial energy does not include the renewable energy from the wind, sun or from various organic waste or biomass materials of plant origin. Nor does it include human or animal produced energy. Since a most critical problem facing the poorer oil importing developing countries is the cost and availability of oil, a useful energy measure is obtained when one refers to barrels of oil equivalent. One barrel of oil equivalent is simply the energy from the combustion of one barrel of oil (calorific equivalence). The cost of this energy can also conveniently be estimated by looking at the world price of imported oil as a first cost and adding related costs associated with the particular process involved. A table of energy equivalences is provided in the front of this report to convert from one energy measurement term to another.

Overview of Energy and Irrigation Relationships

There are three principal parts of the irrigation enterprise where wide variations in energy requirements exist. These are mentioned here and considered in more detail in later chapters of this report. The first is the energy cost of constructing the water supply including the energy cost of the water conveyance and distribution system. The second is the energy cost of constructing the farm irrigation system. The third is the energy cost of operating the irrigation system, this latter being a recurring cost.

In each case the analysis must include the energy cost of manufacturing the materials used in building the system as well as the energy required to construct the works. Except for necessary maintenance, these fixed energy expenditures occur only one time over the life of the system. The energy required to operate the system is a recurring cost, often paid directly by the farmer himself and is, therefore, very important to the poor developing country farmer.

The capacity of each phase of the whole irrigation scheme to keep water losses and wastage low, often referred to as efficiency, bears a direct relation to the energy considerations and therefore requires careful analysis. This fact must be considered with judgment because one can become enthralled with highly efficient schemes which are so expensive as to be beyond the economic reach of most developing country farmers, regardless of how efficient they may be in applying water. This fact must be constantly kept in mind.

Finally, a comment should be made about installed subsurface drainage which is sometimes necessary for successful long term irrigation in arid regions. Whether installed subsurface drainage is required depends on the amount of salt in the irrigation water and the natural internal drainage characteristics of the soil. When installed subsurface drainage is necessary, subsurface conduits (tile or plastic drain pipe) are installed a meter or so below the soil surface. An energy expenditure is required to manufacture the tile or pipe and for earthwork and other operations in the drainage installation. A modest annual energy requirement for maintenance and operation may occur but the magnitude of this will not be as great as for irrigation. Although, to our knowledge, no studies have been made to determine annual energy requirements for subsurface drainage, we estimate that it would not greatly exceed the installation energy for surface irrigation -- perhaps 200,000 Kcal/ha/yr. Therefore, when engineering studies show that installed subsurface drainage is required, its energy implications must be included in any specific analysis of irrigation-energy relationships

Chapter II

ENERGY USE IN THE DIFFERENT TYPES OF IRRIGATION SYSTEMS

Two considerations are important in an overview analysis of energy use in irrigation. One is the energy (direct and indirect) that must be expended to provide the water supply. This is related to the source, whether it be surface water captured in surface storage reservoirs or small ponds or water pumped from the groundwater supply. The second is the energy that must be expended in applying the water in the fields and this relates to the type of farm irrigation system used.

For surface water supplies the energy expenditure is mostly in the construction and maintenance of the storage reservoir or pond and the necessary canal distribution system and associated watercourses. There is little pumping energy required except for occasional lift pumps in the canal system since these systems can often utilize gravity flow from the upstream reservoirs. Of course, if the water is ultimately distributed to the land through a sprinkler system, pumping energy is required to provide the pressure to force the flow through the sprinklers, but that is independent of the water supply and is considered in comparing the various types of farm irrigation systems. The water supply for surface water systems may be distant from the fields to be irrigated and must be transported by canals. This energy cost is part of the energy cost of providing surface water along with the energy cost of constructing the dams for the storage reservoirs.

For groundwater supplied irrigation, the irrigated fields are often directly above the supply so long conveyance is not required, but the water must be lifted to the surface. This requires a great amount of energy because of the vast quantity of water required for irrigation. For example, to irrigate a single hectare of land with 1000 mm (3.3 feet) of water per year from a groundwater source which is 10 meters (33 feet) below the earth's surface requires that 10,000 cubic meters of water weighing 10 million kilograms (10,000 metric tons) be lifted to the surface. The energy equivalence of the work required to do this is 981×10^6 Joules or approximately 0.17 barrels of oil equivalent. This theoretical minimum is equivalent to 27 liters (7.2 gallons) of diesel fuel. Considering a typical diesel pump engine efficiency of 25 percent and a pump efficiency of 55 percent (which for LDC conditions may be high), over 196 liters (52 gallons) of diesel fuel would be required merely to lift the water to irrigate this one hectare from the groundwater to the surface. If the groundwater were three times as deep, i.e., 30 meters, 588 liters (156 gallons) of diesel fuel would be required, a very large amount. At the outset, this illustrates the enormous quantities of energy required to pump water for irrigation from the groundwater aquifer.

Comprehensive data on the amount of irrigation in developing countries which is supplied from surface water and from groundwater are not available. However, the 1969 edition of Irrigation and Drainage in the World provides some information from which to make estimates (34). For example, in India in the period prior to 1961 an estimated two-thirds of the 20 million hectares of irrigation received water from minor irrigation works such as groundwater wells and surface storage ponds or tanks. One-third of the nation's irrigation was from government canals supplied from major water supply reservoirs. That report estimated that by 1969 half the potential 80.9 million irrigable hectares in India would be under irrigation. Considering the tubewell developments in recent years, that country's irrigation supplied from groundwater probably has increased and may now be close to half the total.

In Pakistan in 1966, about four-fifths of the irrigation was reported to be from canals supplied by impounded surface water and one-fifth from wells. Like India, the percentage from wells has undoubtedly increased with the recent extensive tubewell programs. Groundwater may now provide a third or more of the nation's irrigation.

In Mexico, the irrigation from pumping accounted for 16 percent and the remainder from gravity flow from canals. That percentage has likely changed with the advent of more pumps to tap the groundwater.

Although it is not possible to say with certainty, for the pruposes of this report it seems reasonable to estimate that worldwide in developing countries one-quarter to one-half the irrigation is taken from the ground and the remainder comes from surface water in reservoirs and streams. The depth below the surface to the groundwater supplies will vary widely depending on local hydrogeologic conditions. In most cases the depth will range from a few meters below the surface down to a maximum of a hundred meters. Typical depths of water raised by animal power will be a few meters and that raised with power driven pumps will often be greater ranging up to 40 meters or more. While the depth of the groundwater table in the Western United States averages 35 meters with the average pumping lift of 58 meters (51), generally it has not been economically feasible to tap such deep groundwater supplies in developing countries. Many groundwater supplies in developing countries are in alluvial plains and near coasts where water table depths may approximate 5 to 10 meters. These figures will suffice to introduce the principles involved in looking at the energy requirements for irrigation in developing countries.

Energy Cost of Constructing Water Supply Works

It is necessary to determine the energy that is required in providing irrigation water through constructed reservoirs and related canal works or to drill and equip tubewells. This includes all the energy required for the manufacture of the construction materials and equipment and the related energy costs in the construction of dams, irrigation canals or tubewells. These energy expenditures, which include all hidden energy subsidies, are necessary initial energy investments related to the water supply only. They are above those required to construct and operate a particular field irrigation system or to pump the water. Nonetheless, these energy costs must be considered in any complete analysis of energy use in irrigation.

To our knowledge a complete sectorial energy analysis of irrigation has not been made. Therefore, of necessity we resort to indirect approaches utilizing the most recent applicable data which are available. Data from input-output analyses provide a possible starting point. One approach leads to a ratio of total energy input into the particular sector to the dollar level of final output in that sector.

Data of this type are usually country-wide and, unfortunately, most of the data are from developed countries. However, it turns out that some useful data are available on input-output analyses for the construction industry. In our judgment these data provide a reasonable guide since the manufactured materials used in construction, such as cement and metal components, require about the same amount of energy to manufacture irrespective of the country involved. Moreover, such activities as drilling tubewells 30 or more meters deep require machines which operate in about the same way irrespective of the country.

In analyzing the energy use in the Hong Kong food system, Newcombe recognized the energy inputs for irrigation which in that country consists mostly of labor intensive furrow and bucket systems with water provided by diesel driven pumps (60). In his analysis, he did not include the energy costs related to the construction costs of the intricate network of distribution canals, stating that this per annum energy cost was minimal. That view which is held by others seems reasonable since the life of the canals is great and there are minimal annual energy costs for their operation, but it should not be accepted without study. The input-output analyses are useful to test the validity of this assumption.

Developing Surface Water Supplies

Several dams in the world which provide irrigation water were studied. The projects were oftentimes multipurpose, providing benefits chargeable to hydroelectric power development, flood control, municipal and industrial water, navigation and other purposes besides irrigation. Using these data, rough estimates of the dollar cost of the project per hectare irrigated were obtained. Many of these projects were originally found economically justified primarily on the basis of the hydroelectric power generation, but, nonetheless, in this analysis a portion of the project construction cost was charged to irrigation. For large hydroelectric projects, we assumed one-fifth of the published project cost was for irrigation benefits. The assumed life of the projects was 50 years for large projects and 40 years for smaller ones. Project costs were obtained from the literature on the dams and in those cases where the costs did not clearly include the water distribution works, the costs chargeable to irrigation were doubled in an effort to account for that. The land area to be served by irrigation was taken directly from published reservoir project data. Table 3 summarizes these data.

It is readily recognized that the data in Table 3 are not precise because so many estimates had to be made to get a dollar cost for providing surface water for irrigation. Costs such as for the land inundated may not have been included. However, the energy costs in construction, including the manufacture of construction materials and the actual

Table 3 Estimated Costs of Selected Projects Chargeable to Irrigation

Project Name, Country (Date)	Project Cost Millions $	Cost for Irrigation Millions $ 1/	Annual Cost for Irrigation Millions $/yr 2/	Hectares Irrigated Thousands ha 3/	Annual Cost Hectare Irrigated $/ha/yr	Annual Cost Corrected for Canal Cost $/ha/yr 4/	References
Ponnaniar, India (1974)	2.5	0.5	0.01	0.85	11.75	11.75	(4)
Dez Dam, Iran (1963)	150	30	0.60	145	4.14	8.28	(1)
The Snowy Mtns. Scheme, Australia (1964)	880	176	3.52	479	7.35	7.35	(1)
Warsak Dam, Pakistan (1960)	76	15.2	.30	40.5	7.40	7.40	(1)
Yanhee Project, Thailand (1964)	188	37.6	0.75	372	2.02	4.04	(1)
Komati Wier & Mhlume Canal, Swaziland (1965)	3.70	3.70	0.092	12.7	7.28	7.28	(2)
Superior Courtland Diversion Dam, USA (1950)	1.55	1.55	0.039	21.7	1.78	3.56	(3)
Aswan Dam, Egypt (1968)	913	182.6	3.65	350	10.43	10.43	(1)
Sonaichur Project, Bangladesh (1964)	0.215	0.215	0.0054	2.43	2.22	2.22	(5)
Ghulam Mohammed Burage Pakistan (1955)	86.1	86.1	2.15	1134	1.90	1.90	(1)
					Average	6.42	

(See next page for footnotes and references.)

Table 3 Footnotes and References (See Previous Page)

Footnotes

1/ Useful life estimated at either 40 or 50 years depending on the size of the project.

2/ When hydroelectric power is involved, irrigation costs are one-fifth of project cost.

3/ Area is that planned for the completed project.

4/ If water distribution works were not included, the cost is doubled in an effort to account for that.

References

(1) New Horizons Topmost Dams of the World, The Japan Dam Association, Tokyo, Japan, October, 1963.

(2) Olivier, H., Great Dams of Southern Africa, Durnell and Sons, Cape Town, South Africa, (Book undated--late 1970's).

(3) Dams and Control Works, U.S.Bureau of Reclamation, U.S. Government Printing Office, Washington, D.C., 1954.

(4) Balasubramaniam, T.M., Dossaniar Reservoir Project, New Irrigation Era, Public Works Department, Madras, India, 13:2-8, April, 1973.

(5) The Comilla Pilot Project in Irrigation and Rural Electrification, Pakistan Academy for Rural Development, Comilla, East Pakistan, November, 1963.

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construction itself, have been included and, after all, it is the energy invested in the construction with which this aspect of the study is concerned.

With the data available the only way to get estimates of the energy expenditures necessary for the construction of the dam is to use input-output data which relate total energy input (direct and indirect) to dollar expenditure for the final product. Such data are available for many sectors of the economy, but not for the construction of dams and irrigation canals. Input-output data are available for construction of various types including highways. Highway construction involved the use of concrete and steel and moving large quantities of earth such as in dam construction. Therefore, it seems reasonable to use these data for estimating the energy cost of developing surface water supplies for irrigation.

Herendeen and Bullard (43) determined that the primary energy investment in constructing new highways in the U.S. was 111,436 Btu/dollar (1963) of final output in 1963. The figure had changed very little in 1967. Wright estimated the figure to be 105,089 Btu/dollar (1963) for highway construction (82). The figures from Herendeen and Bullard for other kinds of construction were slightly less ranging from 76,000 to 87,000 Btu/dollar (1963). Other data on construction as a whole in West Germany show that these figures for the U.S. are comparable to those in Germany (30). Finally, still another study shows the energy investment (consumption and fixed components) for general construction (not highways alone) in the U.S. to be 64,000 Btu/dollar and to vary little from that in the European countries and Japan (29).

Quite obviously, there is no single figure that relates energy expenditure to dollar invested in final output. However, a figure of 110,000 Btu appears to be a reasonable one for the purpose of this study. The equivalent representations of that figure in other energy terms are 27,720 Kcal/dollar output, 0.020 barrel oil/dollar output, 116 MJ/dollar output, 43.2 hp-hr/dollar output and, finally, 32.2 KWh/dollar output.

The dates of construction of the ten dams listed in Table 3 ranged from 1950 to 1974 with most between 1960 and 1968 giving an average date of construction in the early 1960's. Therefore, using the 1963 dollar value as was the case for most of the input-output studies seems reasonable and inflation since that date will not affect the resulting energy determinations. The average 1963 dollar cost per year per hectare irrigated for the projects in Table 3 is $6.42.

Matsui, in discussing the capital costs of bringing extensive areas in India under irrigation in the second and third plans under the irrigation development schemes of that country, provided estimated costs of the new irrigation and flood control systems (55). Using these projected costs for the irrigation and flood control works and the new areas to be served results in $5.17 in 1963 dollars as the cost per year per hectare of irrigated land served. In this claculation, the life of the irrigation water supply system was estimated to be 50 years and three-fourths of the project cost was charged to irrigation and one-fourth to flood control benefits.

A reasonable estimate of the dollar cost per year per hectare irrigated is the mean of the two figures determined above and is $5.80. This final dollar output figure has an energy equivalent of 706,200 Btu/ha/yr. Comparable barrels of oil equivalent, horsepower-hours, kilowatt-hours and Kilocalories are 0.128 bbl oil/ha/yr, 277 hp-hr/ha/yr, 207 Kwh/ha/yr and 178,000 Kcal/ha/yr. In other words, the annualized energy investment made in the construction of works to provide surface water for irrigation is 0.128 barrels oil equivalent for each hectare to be irrigated.

Developing Groundwater Supplies

Energy also must be invested to drill the wells and manufacture the pumps and power units required to develop groundwater supplies. This is over and above the energy required to drive the pumps when the wells are producing water. These energy costs for developing the groundwater supplies can be expressed as energy required per hectare irrigated in much the same way as was done in the previous section for surface water. Again, direct data on the energy required to drill and equip an irrigation well are not available, so the indirect method of using input-output data must again be used.

In 1975, Johnson obtained data from 192 private tubewell owners in Pakistan (47). This included 109 electric driven pumps, 76 diesel driven pumps and 7 tractor driven units. The sizes of the wells were 4", 5" and 6". In this area of Pakistan the groundwater table was not deep, averaging about 4.4 meters (14.5 feet), and the "boreholes" themselves averaged only 35 meters (114 feet). Johnson calculated the capital cost of constructing and equipping a tubewell on an annualized basis considering the projected life of the various individual components amortized at 10 percent. These costs including annual repair and operator cost were:

Tubewell Size, inches	Annual Cost, $	Water Pumped Annually 10,000 m^3	Estimated Hectares Irrigated 1/	Annual Cost $/ha/yr
4	881	16.0	16	27.5
5	1,168	27.2	27	21.5
6	1,508	43.1	43	17.5

1/ Based on data for average total area served by a single tubewell and the estimated volume of water pumped annually. About one hectare-meter (10,000 m^3) of water is pumped annually per hectare. Cropping intensity for areas served only with tubewells was 124% and was 167% in areas served with perennial canals supplemented by tubewells. Others have also found that areas served by tubewells can have a greater cropping intensity. For example, Narain and Roy determined from a case study in India that areas served with tubewells had a greater cropping intensity than areas served by canals (59)

Yasin reported on tubewells in the Punjab showing that by 1974-75 an estimated 125,000 tubewells would exist with the average area irrigated by each tubewell to be 35 hectares (83). However, these tubewells are not the only source of water for this land since some of the water is supplied by canals. For this calculation, we assume only half the water is supplied from the tubewells making the net area supplied by each tubewell only 17.5 hectares. Yasin reported the capital cost of an average diesel tubewell in 1975 to be about $5,840 and for an electric tubewell about $3,375. If the average life of the tubewell is 12 years, the annual cost per hectare irrigated is $27.80 for diesel tubewells and $16.08 for electric tubewells, using Yasin's data.

Bhatti and Fayyaz in 1973 reported the capital costs of large tubewells drilled 60 meters deep and with 2 cusecs (0.057 m^3/sec) capacity and 107 meters deep and 5 cusecs (0.14 m^3/sec) capacity (21). These capital costs were $9,200 and $14,500 respectively. Tubewells of this size will irrigate larger areas which we estimate to be 24 hectares for the smaller wells and 60 hectares for the larger ones. The annual capital cost per hectare is $31.90 and $20.14 for the smaller and larger wells, respectively, again assuming a 12 year life.

Finally, still another study of tubewells was reviewed, this being for deep tubewells in Bangladesh (3). These costs which were published in 1963 indicated an average capital cost of $6,450 for 6-inch electric tubewells and $4,700 for the same wells powered by diesel engines. The electric tubewell cost included the cost of the 400 volt power line which accounted for 40 percent of the total capital cost. Considering the life of the line to be 40 years and the life of the tubewells and equipment to be 12 years, the annual capital costs for both systems are about $390. If the system serves 30 hectares, the annual capital cost in 1960 dollars is $13/ha/yr. Correcting these figures for inflation makes the capital cost about $23/ha/yr in 1970 dollars.

These various studies show the annual capital cost for tubewell construction and equipment to range from $16.08 up to $31.90 per hectare. In fact, taking a simple average of all the figures gives a useable estimate of $23.27 for the annual capital cost of providing irrigation water to a hectare of land in developing countries. This does not include operating costs and this calculated figure is useable only to estimate the energy investment in constructing tubewells and manufacturing the related equipment.

Much of the capital cost of a tubewell is for the electric motor or diesel engine and the pump, not for drilling the well. Moreover, great quantities of manufactured goods are not required such as for cement in constructing a dam. Four input-output sectors were studied in terms of the primary energy cost per dollar of final output (43). These sectors and their Btu primary energy input per dollar (1963) final output were: Internal combustion engines at 61,750 Btu/dollar output; pumps at 55,256 Btu/dollar output; electric motors at 62,724 Btu/dollar output; and general construction at 88,662 Btu/dollar output. Thirty percent of the cost was assumed to be chargeable to the pump, 30 percent to the motor or engine and 40 percent to general construction (drilling the well), giving a weighted input-output figure for tubewells of approximately 70,000 Btu/dollar (1963) output.

Using the above derived figure, one can now estimate the primary energy input that must be invested before groundwater can be provided to land for irrigation. This figure for tubewells is 1,629,000 Btu/ha/yr which is equivalent to 0.293 barrels oil equivalent/ha/yr, or 640 hp-hr/ha/yr, 477 KWh/ha/yr, or finally, 410,500 Kcal/ha/yr.

Summary of Energy Costs for Developing Water Supplies

In summary, the primary energy cost to develop irrigation water supplied from surface water through large reservoirs or from groundwater through tubewells on an annual basis in various energy units is:

Units	Surface Reservoirs	Tubewells
Btu/ha/yr	706,200	1,629,000
Kcal/ha/yr	178,000	410,500
Barrels oil/ha/yr	0.128	0.293
Hp-hr/ha/yr	277	640
KWh/ha/yr	207	477

In general, according to these calculations, it takes over twice as much primary energy to develop irrigation from groundwater sources as from surface water sources. Moreover, this does not include the energy cost of pumping the water which is a large continuing annual energy requirement. That is one reason why investigators such as Bhatti and Fayyaz report that even farmers with a tubewell would prefer the water from surface canals if the flow, which usually contains water of higher quality, were dependable (21).

Energy Demands for the Various Components of On-Farm Irrigation Systems

Farm irrigation systems require energy in the manufacture of the pipe and equipment used and for the operation and maintenance of the system. The energy invested in the manufacture of the pipe and equipment is made only once during the life of the system while the energy demand for operating and maintenance recurs each year. Oftentimes, only the annual operating energy costs are considered, but any complete energy analysis of energy in irrigation must include all the direct and indirect energy investments that must be made to accomplish the desired objective.

Energy to Manufacture Equipment and Install Irrigation Systems on the Farms

Batty, et al., summarized data on the energy required in manufacturing various materials used in on-farm irrigation and estimated the probable life of various component materials (19, 20). An irrigation pump with diesel engine requires about 1×10^6 Kcal per horsepower to manufacture. An electric motor requires about 0.5×10^6 Kcal per horsepower to manufacture. Similar figures for other components of an irrigation system were determined giving the approximate relations of several types of systems and are shown in Table 4.

Table 4. Annual Fixed Energy Inputs in Thousands of Kcal/ha/yr Required for the Installation of Different Types of Irrigation 1/

Irrigation System	Manufacture of Pump	Manufacture of Pipe and Other Equipment	Earthworking Leveling and Ditching	Total
Surface	16.7	15.5	78.8	111.3
Surface with IRRS 2/	16.7	195.1	79.3	291.1
Hand Moved Sprinkler	20.3	168.8	3.3	192.4
Trickle 3/	17.7	975.5	13.4	1006.6

1/ Adapted from Table 5 of reference (19). Systems are designed to meet a peak water use rate of 8.4 mm/day.

2/ IRRS is irrigation runoff return system.

3/ The trickle system is designed for a permanent orchard crop.

The energy costs in Table 4 are only those fixed costs on a annualized basis for the manufacture and installation of the system and do not include any of the annual operating costs. These latter energy costs are illustrated later in Table 5 where the energy to provide the water supply and pump it are both included.

Energy to Operate On-Farm Irrigation Systems

The primary energy requirement to operate irrigation systems results from the enormous amounts of work required to lift the water from its source to the fields. For gravity systems supplied by surface water, this requirement can be relatively small. However, for sprinkler systems or those in which the water is supplied by deep groundwater zones, that energy requirement is usually quite large.

To lift 10,000 cubic meters of water (about enough to meet the annual demands of one hectare of crops in a semi-arid climate) from a depth of ten meters requires that 10,000 metric tons be lifted 10 meters. The physical energy required to do this is 981 x 10^6 Joules or 23,426 Kcal. However, much more commercial energy than this must be supplied to the pump motor because the systems to convert the heat energy of the fuel to physical energy for moving water are not 100 percent efficient. Diesel engines are about 25 percent efficient in converting fuel to mechanical energy, and electrical systems are roughly the same when the efficiencies of the generating plant (about 34 percent), the power transmission lines (about 85 percent) and electric motors (about 88 percent) are all considered. For example, 0.34 x 0.85 x 0.88 = 0.25, or 25 percent net combined efficiency.

The efficiency of irrigation pumps is an important factor to consider. Seldom do irrigation pumps in the field reach the potential pump efficiencies of about 70 percent that is possible for a well designed pump that is properly matched to its operating conditions. Tests of actual irrigation pump efficiencies indicated that typical efficiencies are between 50 and 55 percent. For example, in Texas an average efficiency of 52 percent was observed (27) and in Idaho nearly two-thirds of the pumps tested had an efficiency of 55 percent or less (76). In Nebraska, most irrigation pumping plants were well below their potential performance (36). Data clearly show that, in the United States, irrigation pumps operate well below their potential and average no more than 55 percent efficient. A realistically achievable efficiency is probably 62 to 65 percent, but to accomplish it would require good management and a very significant capital expenditure for new pumps. If it were done, however, energy savings of 15 to 20 percent could be achieved.

Irrigation pump efficiency in developing countries is likely not as high as in the United States and probably averages about 50 percent or less. Few data are available on tests of irrigation pumps operating in the field in developing countries.

Assuming the irrigation pump that lifts the 10,000 cubic meters of water 10 meters has an efficiency of 50 percent and is powered by a diesel engine (25 percent efficient), then the commercial energy required is 7848 x 10^6 Joules or 1,874,100 Kcal. This is equivalent to the energy in 1.3 barrels of crude oil per hectare per year.

Some data on energy requirements for irrigation in the United States, although not directly applicable to developing countries, are useful to illustrate the extremely high level of energy input into modern irrigation (31). The energy costs for irrigation in the arid and semi-arid western 17 states of the U.S. were calculated for 58 producing regions according to water supply. Forty-five percent of the irrigation is from groundwater and 55 percent from surface water. The groundwater table in the western U.S. is deep averaging 55 meters and the average pumping depth is 58 meters. However, since only 45 percent of the irrigation in the Western United States is from groundwater with the remainder from surface water, the average lift is only 26.1 meters. In the Western United States, on the average it takes 6,026,000 Kcal/ha to provide one meter of water for irrigation with an average lift of 26.1 meters. Since the average water required to irrigate cropland in the Western United States is about 520 mm, the average pumping energy needed to irrigate one hectare of cropland is 3,133,000 Kcal. Remember, these figures do not consider the energy involved in the construction of the irrigation water supply and distribution works -- only the energy to pump and provide the water. These figures compare well with those given in Table 5 and Figure 4 presented in the next section.

Effect of Type of Farm Irrigation System on Energy Requirements

At the outset it is useful to look at calculations that have been made to determine the energy inputs to irrigation for several different kinds of on-farm irrigation systems in the United States (20). These calculations were for two types of surface irrigation, a trickle system and six types of sprinkler systems. Several of these systems are very expensive to install and involve a fairly high level of technology and, as a result, are not easily applicable to the economic circumstances usually found in developing countries. However, the examples are useful because they provide a general comparison of the energy required to provide the energy for several on-farm irrigation systems. The calculations on energy inputs are based on a design to irrigate a hypothetical 64 hectare farm with each of the nine systems.

First, it is important to stress one basic principle. The energy required for irrigation is directly related to the water application efficiency, which is the percent of the water that arrives at the field that is distributed to the crop root zone. If any given system has high water losses through poor design or careless on-farm irrigation practices, that system will waste both valuable water <u>and</u> energy. Some systems such as sprinkler and trickle inherently have greater potential for high water application efficiency, but they too can be poorly managed and, very importantly, they are often well beyond the economic reach of most farmers in developing countries. For the purpose of any comparative analysis of the energy requirements of irrigation, representative typical efficiencies of applying irrigation water must be assumed. In general, the shorter the length-of-run in surface irrigation, the greater the water application efficiency that can be achieved.

Barry and Keller considered an irrigated farm under conditions in which the annual crop water requirements are 915 mm (20). They determined the energy requirements to level the land for a typical farm for surface irrigation and to manufacture and install the pipe and equipment for the various sprinkler and trickle systems. The expected typical irrigation water application efficiencies of the various systems were considered. A simple gravity surface system was assumed to have 50 percent efficiency because of deep percolation at the upper end of the system and the normal runoff at the lower end of the system. If that runoff water was recovered and pumped back to the water supply, the irrigation efficiency was improved to an estimated 85 percent. They assumed water application efficiency of the sprinkler systems to be 75 percent and the trickle system to be 90 percent.

The results show that the surface systems require the least total energy for irrigation. While the surface system with an irrigation runoff recovery system (IRRS) was most efficient over a wide range of pumping lifts, because of its higher irrigation water application efficiency, the surface system without IRRS proved more energy efficient than sprinkler systems except for very high pumping lifts of about 100 meters or more.

A similar study in Oregon used simulation techniques to compare the energy requirements of various kinds of irrigation systems (81). Again, surface irrigation was compared with drip irrigation and various kinds of sprinkler systems. In the Oregon study, the surface irrigation system was found to be by far the most energy efficient for the various conditions considered, even when the substantial energy costs for land leveling were considered. The trickle system was second and the sprinkler systems were the least energy efficient. The sprinkler system always suffered in the comparisons because of the high energy requirements to provide the high water pressures required to force the water through the sprinkler nozzles.

Using the energy costs of developing and providing irrigation water from surface water and groundwater sources along with the total energy cost of installing and operating the irrigation system, Table 5 is developed. Table 5 uses the data on energy costs for installing and operating systems from Batty and Keller and the energy costs which we have calculated for developing the water supply from surface water and groundwater sources (19).

The surface irrigation design in the Batty and Keller study considered furrows with lengths-of-run in most cases 400 meters which are much longer than typically exist in developing countries. For these United States systems with very long irrigation runs, the assumed irrigation water application efficiency of 50 percent is reasonable. However, with good management and smaller fields with shorter lengths-of-run, the water application efficiency could be increased to 70 percent or more. Therefore, a second calculation was made in Table 5 for a surface irrigation system with an application efficiency of 70 percent. This efficiency is reasonably obtainable if the farmers have well leveled fields and employ good on-farm water management practices. A third surface irrigation system evaluated had an irrigation runoff return system (IRRS) and this system, more costly to install, had a high irrigation efficiency of 85 percent. The trickle system is very efficient but quite expensive to install and requires careful maintenance and, therefore, is not considered practical for most LDC conditions. The hand moved sprinkler system is also costly and not practical under most developing country circumstances.

When water is pumped from great depths, poorly managed surface irrigation systems with low irrigation efficiency are not energy efficient because of the great quantities of water that are wasted. Figure 4 graphically shows the same information as provided in Table 5 and can be used to determine the annual energy inputs required for one meter net irrigation for any water lift from zero to 100 meters.

Table 5.[1] Comparison of the Annual Energy Required to Provide Net Irrigation of One Meter by Four Systems from Surface Water and Groundwater with Lifts of 50 Meters and 100 Meters. Energy Figures are in Thousands of Kcal/ha/yr.

			Surface Water Supply			Groundwater - 50m Lift			Groundwater - 100m Lift		
	Irrigation Efficiency	Installation Energy	Energy to Provide Supply	Pumping Energy	Total Energy	Energy to Provide Supply[3]	Pumping Energy	Total Energy	Energy to Provide Supply	Pumping Energy	Total Energy
Surface Irrigation (50)	.50	111	178	760[2]	1,049	308	13,432	13,850	410	26,105	26,626
Surface Irrigation (70)	.70	111	178	543[2]	832	308	9,594	10,013	410	18,646	19,168
Surface Irrigation with IRRS 4/	.85	291	178	746[2]	1,215	308	8,200	8,799	410	15,654	16,355
Hand Moved Sprinkler	.75	193	178	8,955	9,326	308	17,403	17,904	410	25,851	26,454
Trickle 5/	.90	1,006	178	4,928	6,112	308	11,985	13,299	410	19,008	20,424

1/ Data in this table adapted from reference (19). Systems are designed to meet a peak water use rate of 8.4 mm/day. Also, note that in making the pumping energy calculations, Batty and Keller assumed the pump efficiency = 0.70 and the net pump power unit efficiency = 0.264 giving a combined irrigation pumping unit efficiency of 0.70 x 0.264 = 0.185. These figures are typical of the most efficient pumping units possible. In many cases, irrigation pumps in the field have efficiencies of only 0.50 and the pump power unit efficiencies of about 0.24, giving combined irrigation pumping unit efficiency of 0.12. Therefore, the values of pumping energy are the lowest possible and they could be increased by as much as 50 percent or more if less efficient pumping units were used.

2/ Some pumping energy is assumed even for surface irrigation with open ditch to account for friction head loss in pipe and a slight elevating of the water to the level of the ditches. In systems where canal water is supplied at sufficient elevation to permit gravity flow, pumping energy is zero except for the modest amount of energy required for the system with an irrigation runoff recovery system (IRRS).

3/ Energy to provide supply (drill and equip the well) for a well with 50 meter pumping lift was estimated to be 75 percent as much as for a deeper well with 100 meter pumping lift.

4/ IRRS is an irrigation runoff recovery system.

5/ Trickle system is designed for orchard crops.

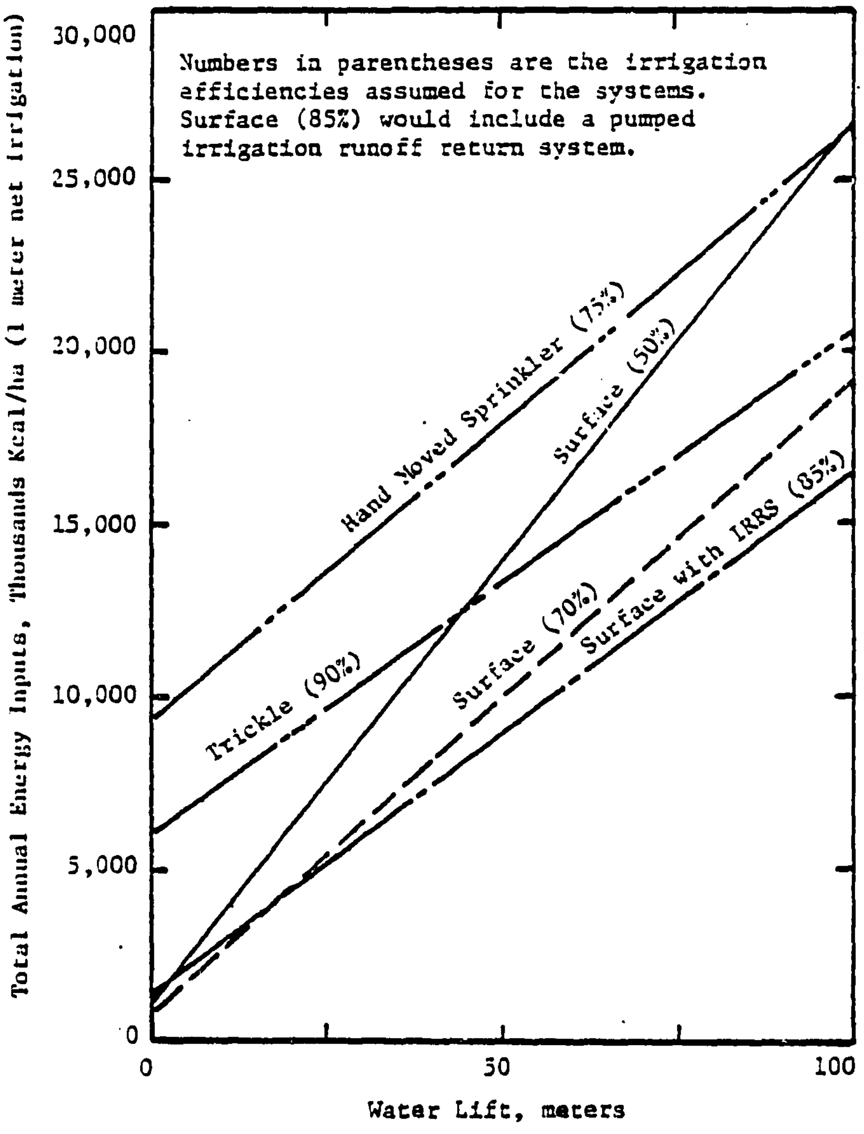

Figure 4. Total annual energy requirements for different irrigation systems related to pumping lifts.

As far as water source is concerned, when surface water is available, it normally can be developed with less energy expenditure than drilling wells and developing the groundwater resources. However, in either case the cost of developing the water supply is not large compared to the cost of pumping water, even when the pumping lifts are small. For the two surface irrigation systems without irrigation runoff recovery systems included in Table 5, the percent of the total energy for irrigation which is required to develop a surface water supply is from 17 to 21 percent. When the systems are supplied by groundwater, the total energy to provide the supply is greater than for surface supplies, but the percent of total energy chargeable to developing the water supply, i.e., constructing the well and manufacturing its equipment, is less than 4 percent. In fact, when these surface irrigation systems are supplied from groundwater with lifts of 50 to 100 meters over 96 percent of the total energy required is for pumping. This strongly indicates that pumping is the predominant energy requirement for irrigation. Furthermore, a general conclusion can be drawn that the energy requirement for irrigation will be affected little by errors or slight changes in the energy input determinations for providing the water supply or for installing the system. These results also tend to confirm Newcombe's assertion mentioned on page 9 that the per annum energy cost of constructing the water supply networks is minimal (60).

In the sections which follow, examples are presented in the form of case studies to illustrate the concepts presented. Data for these case studies came from developing countries.

Energy for Land Leveling -- Case Study

Land leveling is a major factor in improving the efficiency with which irrigation water can be applied. The energy cost of leveling land for irrigation is dependent on the size and topography of the fields and the equipment available to do the land leveling. The topography will vary for steep mountains, where narrow bench terraces may be constructed with human labor, to alluvial plains where the smoothing and leveling of uneven fields may be done by machines. This case study from Pakistan is for conditions typical of alluvial plains (8, 67).

Studies have indicated that when farmers irrigate unleveled fields, overirrigation generally results because of the natural tendency of farmers to keep irrigating until the high spots become wetted. Under traditional conditions in Pakistan without precision land leveling, it was found from a study of 52 sites that over 70 percent of the sites were overirrigated resulting in the loss of valuable water and leached nutrients. The process resulted in excessive energy costs. Sometimes the gross amount of water applied to poorly leveled fields was 3 to 4 times the desired application.

In the Mona Project in Pakistan a land leveling survey indicated that only one-fourth of the land satisfied a criterion of individual field basins being leveled to 0.03 meters maximum elevation difference. Another survey indicated even fewer fields met this levelness criteria (48).

Calculations of the total commercial energy required to level fields were made considering the volume of earth moved and the average distance the earth was hauled. For two cases the energy requirement is about 10.3×10^6 Kcal/ha for a 0.95 hectare field and 4.26×10^6 Kcal/ha for a 2.1 hectare field. In these cases either a 48 or 64 horsepower tractor and scraper were used in the work and the energy to manufacture and operate the machines were both considered. For comparison, in another study Batty and Keller in the United States found the land leveling energy for a 64 hectare field to be about 3.15×10^6 Kcal/ha (19). This wide variation is not surprising since the local topography of fields to be leveled is so different.

If for purposes of illustrating the energy cost of providing land leveling in developing countries we conservatively use the large figure of 10×10^6 Kcal/ha for the leveling energy and charge that energy cost over a 40 year period, the result is an annual cost of initial leveling of 0.25×10^6 Kcal/ha/yr. There is an energy requirement to maintain the leveled fields which will be much less than the annualized energy cost of the original leveling. Assuming this maintenance energy to be four-tenths of the annual energy cost for land leveling, provides an annual energy cost of land leveling. This estimated value of 0.35×10^6 Kcal/ha/yr is conservative and should be applicable to typical small fields in alluvial plains using small tractors and scrapers for the leveling operation. It is apparent that the energy investment in land leveling on an annual basis is small and provides a large potential energy savings through more efficient irrigation.

Actual surveys of farmers in Pakistan with precision land leveling indicate that they noted several benefits from land leveling, the major ones being reduced time to irrigate fields (indicating that less water was being wasted) and higher yields (67). The land leveling pays off in several ways and water savings with attendant energy savings is major among them.

The Matter of Installing Concrete Lined Ditches or Underground Pipe

The concept of improving and modernizing surface irrigation systems by replacing open ditches with buried pipelines has frequently been proposed. Pilot projects such as in Sri Lanka have been started in which concrete underground pipe is to be used (57). One major benefit anticipated is to improve the control of water so it can be applied on demand as opposed to a rotation schedule using open ditch watercourses. Water losses also will be reduced permitting better production on farms, particularly at the low end of the watercourse system.

Batty, et al., provides data on the amount of material in various kinds of underground irrigation pipe as well as for concrete lined irrigation channels of different sizes (19). Although it has not yet been done, the energy cost of manufacturing and installing these kinds of water supply systems could be calculated for specific designs under developing country conditions. Nonetheless, some generalizations are possible based on the economic analysis of the benefits to be accrued from these systems.

The mass of material (concrete) used for pipes and lining canals is not great on a per hectare served bases. Neither is the quantity of earth to be moved in the excavation for trenches for pipes or the ditches. Although the dollar cost may be large, the annualized energy investment is relatively modest indicating that economic considerations as opposed to energy factors will likely determine the feasibility of the systems. The amount of water that can be saved, however, is great and can amount to half or more. The economics appear to be favorable even under developing country conditions if the necessary credit and resources are available (50, 57).

In most developing countries, concrete pipe will usually be a readily available material at reasonable cost. Using the bid contract prices for installing the underground concrete pipe for a project under construction in Sri Lanka and the original estimated price for installing concrete lined canals along with input-output data for construction with concrete products, one can roughly estimate the energy investment required to install either underground concrete pipe or lined canals for this pilot project (57, 78). On an annualized basis, assuming the life of the systems to be 40 years, results in about 800,000 Kcal/ha/yr to install concrete pipe and 450,000 Kcal/ha/yr to put in concrete lined canals. These estimates are for a pilot project of only 134 hectares and are probably much higher than will result if widespread use of underground pipe or lined canals were to be installed since the energy costs estimates were indirectly determined using the contract bid price. A more reasonable estimate is likely less than half these values. However, considering the value of the water saved, which is estimated to be as much as 50 percent, the installation of concrete pipe or lining of the canals can often be justified on an energy basis as well as on an economic basis (50, 57, 65).

A critical question that must be considered is whether the capital to improve and modernize the watercourse can be made available and if the scope of such projects can lead to economics of scale in installing the improvements. Great benefit can accrue by having better water control permitting the use of an irrigation schedule which can provide water on demand.

<u>Case Study on Improved Water Management in Pakistan</u>

This case will illustrate the energy that can be saved through good water management practices, such as precision land leveling and watercourse improvement, and comes from a study of private tubewells in the Salinity Control and Reclamation Project (SCARP) (47). The study included 192 tubewells, about 30 percent of which were on land also served by canals and 70 percent on land unserved by canal water. The drilled depth of these wells was shallow, being only 35 meters and the pumping lifts were not great -- about 10 meters. For these wells the total dollar cost of pumping water in the mid-1970's amounted to approximately $65 per hectare-meter and is even higher now. Forty percent of these dollar costs, or about $26 per hectare-meter, were for energy to drive the pumps For these tubewells an average of 30 percent of the costs were fixed annual costs and not related to the quantity of water provided. Therefore, 70 percent of the costs are variable and proportional to the quantity of water pumped.

Early estimates of water losses in watercourse conveyance in Pakistan made by Pakistani agencies in 1964 indicated losses of only 10 to 15 percent (51). These studies by the Lower Indies Project (LIP) and the Irrigation Research Institute-Punjab (IRI) led to the comforting, but later proven erroneous, conclusion that watercourse losses from canals of 1500 meters average length amounted to no more than 10 percent of the water passing through them. However, more recent extensive measurements on over 600 sections of 51 watercourses by teams from the Water and Power Development Authority (WAPDA) and Colorado State University (CSU) showed losses ranging from 4 percent to 72 percent per 305 meters (1000 feet) of watercourse (9). The inflow-outflow method used by the WAPDA-CSU teams included losses at junctions and outlets, losses through rodent holes, etc., and therefore represented all the normal losses in watercourse operation. The losses measured by the ponding method used by the LIP and IRI groups measured only percolation losses under ideal conditions because leaks at junctions or through rodent holes were sealed or avoided. The WAPDA-CSU team found that about half the water supplied to watercourses was lost before it reached the farmers' fields, a far greater loss than originally thought.

The CSU On-Farm Water Management Project efforts, in cooperation with Pakistani cooperators, resulted in several canals being cleaned and renovated (51). The resulting increase in the water delivery efficiency ranged from 21 percent, to 50 percent and averaged from 30 to 40 percent. This cleaning and maintenance was done by the farmers themselves and, therefore, little expenditure of purchased commerical energy was involved. In general, approximately 1.1 meter of watercourse could be cleaned and renovated with hand tools per man-hour of labor. The cost was about $0.12 per meter at the Pakistani labor rate of one rupee per hour. The energy input for labor is 300 Kcal/man-hour making the energy cost per meter of improved watercourse an insignificant 273 Kcal/meter of canal. The energy cost per hectare served on an annual basis is 5000 Kcal/ha/yr. The process is labor intensive and economically justified and is not energy costly. This illustrates that the human labor energy input is not significant in energy calculations, but there are limits to what can be accomplished with human labor in irrigation.

In general, the watercourse improvements in Pakistan reduced the watercourse losses from about 50 percent to about 30 percent. As a result, instead of receiving only 50 percent of the pumped water at the fields, 70 percent was received -- a 40 percent increase in the water for irrigation. The efficiency of the canals in delivering water changed from 50 percent to 70 percent. Even a lesser improvement would be very beneficial and worthwhile in terms of energy savings.

Losses in the actual field irrigation practices also can be of sizeable magnitude. Several conclusions can be made from a study of land leveling in Pakistan (48). Field irrigation application efficiency is a measure of the portion of water received at the field that is delivered by the farm irrigation system to the plant root zone where it can be used by the crop. It will vary from 60 percent for fields with ±5 cm in levelness up to 88 percent when that variation is only ±1cm. The data from 24 precision leveled fields compared to 26 traditionally leveled fields showed that it took only about 60 percent as much time to irrigate the precision fields as the traditionally poorly leveled fields and at the same time the yields increased significantly. Calculations from these studies indicate that the field irrigation application efficiency increased from about 65 percent with traditional leveling to about 80 percent with precision leveling. The dollar cost of the leveling was about $170 per hectare for moving an average of nearly 200 cubic meters of earth per hectare. The energy cost for this land leveling by machine can be estimated to be about 350,000 Kcal/ha/yr (see case study on energy for land leveling). It will be less if more labor intensive methods are used.

For this tubewell case study, one can calculate the energy cost to provide 0.6 meters of net irrigation during the year to a crop in Pakistan. If this irrigation water is transmitted from a tubewell through a poorly maintained watercourse with 50 percent loss (watercourse conveyance efficiency of 50 percent) and applied to traditionally leveled fields with a field application efficiency of only 65 percent, then 1.85 hectare-meters of water must be pumped for each hectare irrigated. However, if the canal is renovated and improved reducing watercourse losses to 30 percent (watercourse conveyance efficiency of 70 percent) and the small fields precision leveled to increase field application efficiency to 80 percent, only 1.07 hectare-meters of water must be pumped to provide the necessary irrigation. About 40 percent savings in pumping energy results along with the same savings in other variable costs. Table 6 illustrates the possible savings in total energy in tabluar form, taking into account the energy cost for the various improvements.

Table 6. Example from Case Study for Irrigation from Tubewells in Pakistan. Energy to Irrigate Crop in Pakistan from Tubewells with 0.6 Meters Net Irrigation. Energy Figures are in Thousands of Kcal/ha/yr. 1/

Irrigation Practices	Water Pumped	Energy to Improve Watercourse	Energy for Precision Leveling	Energy to Pump	Total Energy	Energy Saved by Improvements
	Meters^3	1000 Kcal/ ha/yr	1000 Kcal/ ha/yr	1000 Kcal/ ha/yr	1000 Kcal/ ha/yr	Percent
Unimproved Watercourse Traditional Leveling	18,500	0	0	3,150	3,150	0
Unimproved Watercourse Precision Leveling	15,000	0	350	2,555	2,905	8
Improved Watercourse Traditional Leveling	13,190	5 2/ (200) 3/	0	2,246	2,251 (2,446) 3/	29 (22) 3/
Improved Watercourse Precision Leveling	10,710	5 2/ (200) 3/	350	1,824	2,179 (2,374) 3/	31 (25) 3/

Table 6. Footnotes (See Previous Page)

1/ Pumping energy calculated assuming diesel powered pump with 10 meters total lift as in case for tubewells in Pakistan. Pump efficiency is assumed to be 55 percent and energy efficiency of diesel engine to be 25 percent. NOTE: Pump efficiencies may be higher, up to 70 percent but numerous measurements of irrigation pumps have shown typical efficiencies of about 50 percent, so the assumed 55 percent is reasonable.

2/ This is based in this case study on watercourse renovation by hand labor in an LDC giving a very low value of energy input. If renovation was by machine, the value would be higher and perhaps 200 Kcal/ha/yr.

3/ Total if watercourse improvement was by machine at 200 Kcal/ha/hr.

This actual case study strikingly illustrates again that the best way to save energy in irrigation is to provide management practices which minimize water losses to the maximum extent possible. In this case, the programs to renovate canals to conserve water are also very effective in conserving the energy required for each hectare irrigated and can result in about 30 percent reduction in the annual energy required to irrigate each hectare of land. This case is for one crop per year. If two crops are produced each year (cropping intensity equals 200%), as is possible in tropical and subtropical climates, the benefits of precision land leveling and watercourse improvement are more striking since the energy savings through reduced water pumped occurs for each crop.

It so happens that in many situations there is inadequate water to properly irrigate the available land. Therefore, the water saved can irrigate more land and more food can be produced, all with the same total expenditure for energy for the operation of the tubewell. Regression analysis of a series of tests on the economics of precision land leveling in Pakistan indicates that precision land leveling in fields with from 0.06 to 0.12 meters minimum-maximum elevation range resulted in a wheat yield increase of 499 kilograms per hectare due to leveling (48). Added to this is the production that can be expected from the increased area that can be effectively irrigated because the improved field irrigation efficiency which results from precision leveling permits more land to be irrigated with the available water. In fact, the small plot research data indicate a potential yield increase of 30 percent per hectare possible with precision land leveling and a 72 percent increase in the area irrigated from a given tubewell supply as a result of the combination of precision land leveling and watercourse renovation. Taken together, this illustrates the yield of food per unit of water may potentially be more than doubled. Stated another way, each unit of commercial energy committed to food production could possibly be made to produce twice as much food if the land is available for the additional irrigation. The same result can be achieved in some cases by increasing the cropping intensity on existing land. For this reason improvements in on-farm water management practices must be given high priority in any national strategy for energy in irrigated agriculture.

Energy Savings Possible

The potential energy savings in irrigation is summarized by Gilley and Watts (36).

Their comprehensive report addresses the potential energy savings from various improvements possible in on-farm irrigation systems and presents curves and tables.

The energy required for pumping increases directly in proportion to total pumping lift and also in proportion to the water lost in each component part of the irrigation system. The places where losses occur are along the watercourse and in the fields as deep percolation or as runoff. When the water losses are reduced by a certain percentage, the pumping energy is reduced by a similar amount. We can summarize by considering the general reduction in energy required by two improvements that are readily possible in developing countries -- first, reducing water losses in the canals and watercourses and, second, reducing the losses in the fields during irrigation. A general inverse relationship exists between the energy required for pumping and the efficiency of each component of the overall irrigation system in performing its function. That relationship is shown in Figure 5 in which a Pumping Energy Factor, PEF, is correlated to Efficiency, Eff. If there is no water lost, Eff = 1.0, and the PEF is also 1.0 which is the lowest possible. As losses increase, Eff goes down and PEF goes up. The relationship is simply PEF = 1.0/Eff.

Figure 5, or the above simple inverse relationship, can be used to calculate the effect on pumping energy of any changes which improve the efficiency of a component of the irrigation system. For example, if the efficiency of the watercourse is improved from 0.5 to 0.7 (losses in the watercourses are reduced from 50 percent to 30 percent), PEF for that component is reduced from 2.0 down to 1.43, resulting a 28.5 percent energy savings. If the efficiency of applying water in the fields was increased from 0.65 to 0.80, the PEF for that component of the irrigation system would drop from 1.53 to 1.25, providing an additional 18.3 percent energy savings. A pump might be repaired or replaced, improving its efficiency from 0.55 to 0.67 giving a change of PEF for that from 1.82 down to 1.49, giving still another 18.1 percent energy savings. The total effect on pumping of any combination of changes is the product of the individual PEFs. In the above case the combined PEF before the improvements was

$$PEF_{\text{before}} = 2.0 \times 1.53 \times 1.82 = 5.57$$

After the improvements it is

$$PEF_{\text{after}} = 1.43 \times 1.25 \times 1.49 = 2.66$$

In other words these changes which are reasonably possible reduced the pumping energy requirements to only 48 percent of what it was before, i.e., 2.66 ÷ 5.57 = 0.48. Clearly, the first priority in saving energy is to reduce all losses and improve the efficiency of each component insofar as possible.

The above example can be illustrated in another way by writing a general equation representing the potential energy savings that are possible through improvement of various components in the irrigation system. Such an equation can be expressed as

$$PES = 100 \left[1 - \left(\frac{Eff_b}{Eff_a}\right)_1 \left(\frac{Eff_b}{Eff_a}\right)_2 \left(\frac{Eff_b}{Eff_a}\right)_3 \cdot \cdot \cdot \cdot \cdot \left(\frac{Eff_b}{Eff_a}\right)_n\right]$$

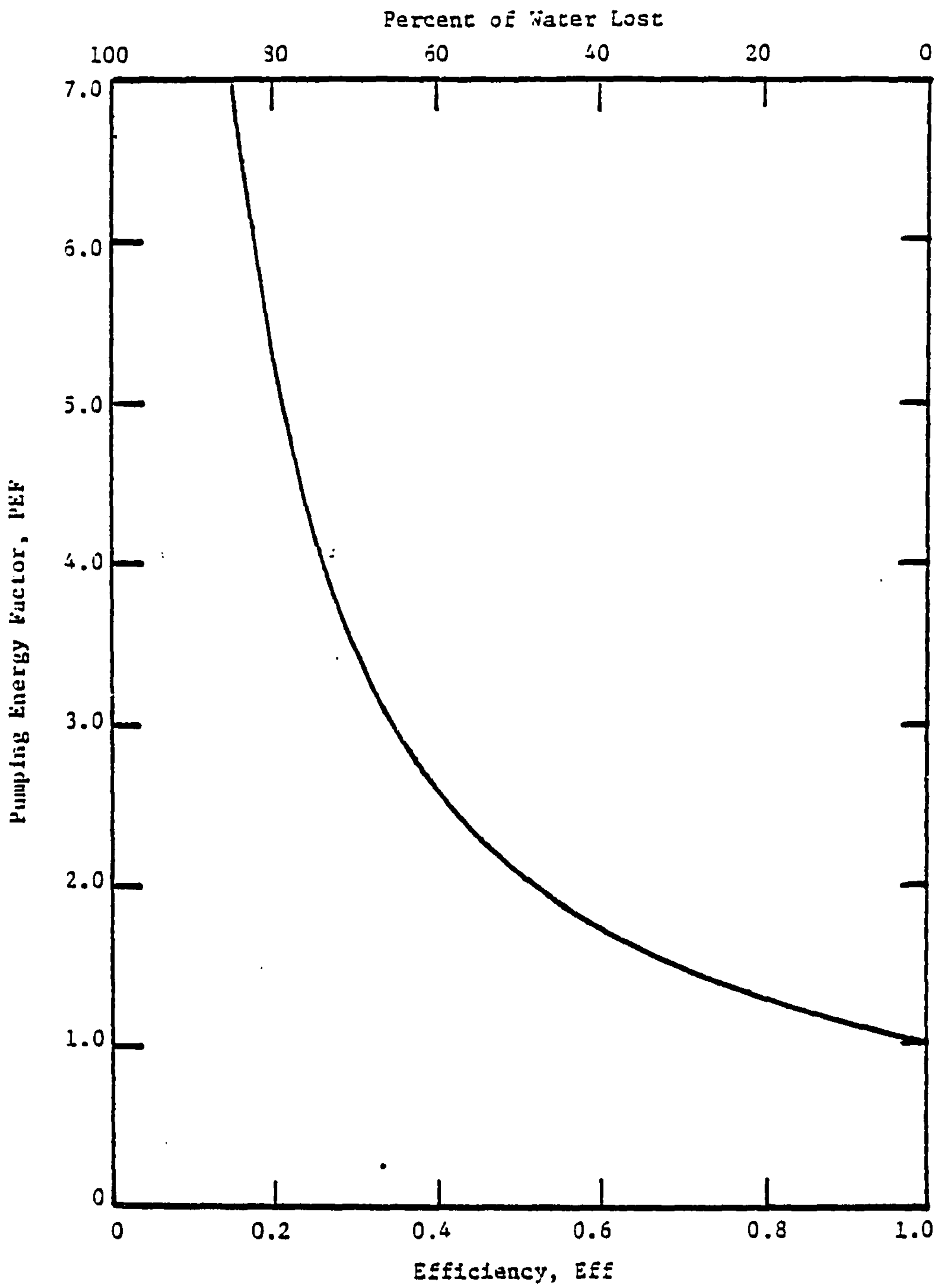

Figure 5. Relationship between efficiency and pumping energy

in which PES is the potential energy savings, expressed as a percentage, resulting from improvements in the efficiency of various components in the irrigation system. In each case the subscript b following Eff within the parentheses indicates the efficiency of that component before improvement and the subscript a indicates the efficiency after improvement. The subscripts "1, 2, 3, ...n," outside the parentheses refer to the individual components of the irrigation system that may be changed to improve efficiency. These include pump efficiency, efficiency of the watercourse system in conveying water without losses and the application efficiency of the field irrigation system in distributing the water that arrives at the field to the soil root zone where it can be used by the crop.

Using this equation for the same example cited above would give $\left(\frac{Eff_b}{Eff_a}\right)_1$ for watercourse losses as $\left(\frac{0.5}{0.7}\right)$

$\left(\frac{Eff_b}{Eff_a}\right)_2$ for efficiency of applying water in the fields becomes $\left(\frac{0.65}{0.80}\right)$

And, finally, $\left(\frac{Eff_b}{Eff_a}\right)_3$ for pump efficiency becomes $\left(\frac{0.55}{0.67}\right)$

In equation form the percentage energy savings, PES, becomes

$$PES = 100\left[1 - \left(\frac{0.5}{0.7}\right)\left(\frac{0.65}{0.80}\right)\left(\frac{0.55}{0.67}\right)\right]$$

$$= 100\left[1 - 0.48\right] = 52\%$$

Therefore, as before the energy savings resulting from the above three improvements is 52 percent or, stated another way, only 48 percent as much energy is required after the improvements are made.

An expanded version of the above equation to include the effect of pumping lifts and the depth of irrigation water applied is developed in APPENDIX II.

Summary

The matter of establishing priorities for making decisions on how to best save energy in irrigation needs summarizing. This may be done in very general terms by looking at the flow of water from the source to the field, figuratively speaking, and identifying the general magnitude of energy use in each component and the potential energy savings possible. One can look at the elements shown schematically in the following:

$$\boxed{\text{Water Supply}} \rightarrow \boxed{\begin{array}{c}\text{Irrigation}\\\text{Water}\\\text{Conveyance}\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Farm}\\\text{Irrigation}\\\text{System}\end{array}} \rightarrow \boxed{\begin{array}{c}\text{Farm}\\\text{Irrigation}\\\text{Management}\end{array}}$$

At the outset it is important to reiterate that only general guides can be given because each irrigation situation is different from any other. No two regions of the world have the same hydrology and topography and surface water storage potential, the same hydrogeologic conditions and groundwater potential, the same soils and topography for canal construction and field irrigation, the same climate and rainfall distribution, the same potential for multicropping, or the same socio-political institutions for irrigation management. Some irrigation is in large projects and in other cases, it will be in small individually supplied, single farm irrigation units. Moreover, there will be exceptions to any general recommendation that may be given. However, the generalizations given will provide understanding of irrigation-energy relationships and guidance for those who must make decisions regarding the best way to save energy in irrigation under any specific set of circumstances.

It must always be remembered that one cannot isolate energy consideration from economic cost data. Nor can one separate an assessment of operations and maintenance problems associated with a potential new technology from judgments on the likelihood of the essential support services being available on farms in developing countries.

Each of the factors will be considered separately.

Water Supply

The decision on whether surface water supplies or groundwater supplies are developed will generally be based on hydrologic factors indicating which supply is available as well as on economic and financing considerations. Surface water quality is usually better, but the canal supply system usually operates on a rotation basis and does not have the flexibility of supply-on-demand to individual farmers that tubewells provide. Tubewell irrigation often enables greater multicropping because water can be supplied on demand. Surface water reservoirs cannot be constructed in phases as is the case for tubewell irrigation, so the entire project financing must be available before construction can begin.

These are only a few of the factors, other than energy considerations, that affect the decision concerning the water supply. However, when energy alone is considered surface water projects require less than half as much energy to provide the water on a per hectare per year basis, 178,000 versus 410,500 Kcal/ha/yr. Furthermore, when groundwater is used there is the recurring annual energy requirement for pumping and this depends on the depth of the water below the earth's surface.

Irrigation Water Conveyance

Water which is lost in its conveyance from the supply to the fields results in a direct loss of the energy invested in providing the supply. Therefore, controlling losses in water conveyance is an important first step in saving energy.

In Pakistan, it has been shown that earthen watercourses could be improved to reduce water losses from 50 percent to 30 percent. This required an energy investment of only 5,000 Kcal/ha/yr when the watercourse renovation was by hand labor with hand tools and an estimated 200,000 Kcal/ha/yr if done by machine. In either case it is a small energy investment for the water and energy saving benefits received and it is well justified.

There is little data from developing countries on the energy requirements for providing concrete lined canals or concrete underground pipe. However, based on a pilot project in Sri Lanka, we estimate that the energy to provide concrete lined canals would be no more than 225,000 Kcal/ha/yr if the practice were to be implemented on a widespread basis. Similarly, underground concrete pipe irrigation systems if widely used could be installed for an estimated annualized energy commitment of less than 400,000 Kcal/ha/yr. In the case of concrete lined canals or concrete underground pipe, the existing water losses would essentially be eliminated. The economic justification for such improvements appear favorable, but that will depend on the individual cases and the availability of capital and credit and, therefore, no general conclusion can be reached.

However, it is evident that great energy savings can result in watercourse improvement. Renovation of existing earthen watercourses is a wise decision if water losses are occurring. In many cases, it is probable that the further improvement with concrete canals or underground concrete pipe can be justified from an energy point of view. However, the economic justification will control in most cases and this requires careful study of each individual case.

Farm Irrigation Systems

Improvement of irrigation management practices on the farm provides great opportunity for energy savings. Surface irrigation systems require much less energy for installation and operation than either sprinkler systems or trickle systems. The surface systems are the best from an energy use point of view except for groundwater supplied systems when the pumping lifts are very great -- approaching 100 meters (a depth of water rarely found in developing countries). As a general rule, surface irrigation systems will be the best suited for developing countries.

For the small farmers typically existing in developing countries, the irrigation application efficiency can be expected to reach 70 percent, if the irrigated land is accurately leveled. This is possible because the irrigated fields typically are small and the length-of-run in the fields is small. When the length-of-run is large, such as is typical for the United States, irrigation runoff recovery systems are justified on an energy basis.

Precision land leveling is the most easily achieved improvement in farm irrigation practices in developing countries. The annualized energy cost for land leveling is 350,000 Kcal/ha/yr or less and, considering the improvement in the irrigation application efficiency that can result, it is well justified on an energy basis. The case study reported for Pakistan, summarized in Table 6, illustrates the value of land leveling in a striking manner.

Farm Irrigation Management

Farm irrigation management covers the many management factors which ultimately control the success of any energy efficient and successful irrigation system. The farmer must understand the places within the irrigation system where water losses, and resulting energy losses, occur. He must be advised on practical irrigation management practices to help him achieve the goal of an energy efficient irrigation operation. This requires support of local educational programs appropriate to the individual conditions to assist the farm irrigators in understanding the benefits that can result in good farm irrigation management practices. It is unrealistic to expect that the energy savings possible with good irrigation will be realized on a significant scale unless good educational programs, designed for the local socio-political setting, are implemented.

Chapter III

ALTERNATE RENEWABLE ENERGY TECHNOLOGIES WITH POTENTIAL IN LDC IRRIGATION SYSTEMS

Many of the developing countries depend heavily on fossil fuels for energy, and even in cases where they have significant fossil fuel resources, they are often short of the financial resources to develop them. Thus, on the whole, these developing countries derive more than half of their total energy from wood and agricultural or animal wastes (12). As modernization and energy requirements of these countries increase, the efficiency of the development and use of critical energy resources will be vitally important.

With regard to irrigation, the convenient and predominant power sources have been oil and gas used in internal combustion engines and electricity, often derived up to now from fossil fuels. Electricity derived from hydroelectric plants is an important source where water resources and sites suitable for hydropower are available. In the long term, local applications of biomass, solar, wind and other renewable energy forms may hold promise of more abundant energy, but the economic costs should not be underestimated.

This chapter provides a brief discussion of several alternative energy conversion technologies that may have potential for use in irrigation in developing countries. Chapter IV analyzes the advantages and shortcomings of the various alternate renewable energy sources.[1/] Discussed in this chapter are agricultural biomass,[2/] solar and wind energy conversion technologies. Biomass technologies considered are direct combustion, gasification and pyrolysis of plant residues; methane production by anaerobic digestion of animal wastes; ethanol (ethyl alcohol) production from starchy and sugary crops; and production of a diesel-fuel substitute from plant oils.

Direct Combustion, Gasification, and Pyrolysis of Plant Residues

As discussed here, "direct combustion" refers to burning of the biomass in an excess of air. In "gasification" the oxygen supply is restricted resulting in occurrence of incomplete combustion releasing combustible gases such as carbon monoxide, hydrogen and methane. "Pyrolysis" is the transformation of an organic material into another form by heating in the absence of air; principal products of pyrolysis are gases, oils and char.

Conversion systems are of a thermochemical type and are classified as nonbiological, dry processes. Exhaustive descriptions of the conversion systems, environmental impacts, and economics related to combustion, gasification and pyrolysis have been presented in a recent publication of the Office of Technology Assessment (OTA) of the Congress of the United

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1/ The reader who is only interested in the advantages and shortcomings of the various possible renewable energy sources, and not a review of the various processes may go directly to Chapter IV.

2/ Biomass, a form of solar energy resulting from the growth of plants or microorganisms, includes all organic matter except fossil fuels. Dry biomass contains about half as much energy as coal -- 3900 Kcal/kg.

States (13). Thus, only a condensed description of the technologies will be given here.

Direct Combustion

Technology for direct combustion is highly developed and in wide use commercially with wood as the feedstock. Systems are available for production of electricity or steam or for cogeneration (simultaneous production of steam and either electricity or mechanical shaft power). Much research is underway to develop suitable combustion systems for high-moisture agricultural biomass residues (e.g. rice hulls, cotton gin trash, grain stover, etc.) and to study optimum particle size, feeding systems, particulate control, suspended burning systems, etc. (74).

The conversion system consists of a reactor (furnace) to convert the biomass to heat, a boiler to convert the heat to steam, and a turbine to convert the steam to electricity. In the reactor, provisions must be made to: (a) introduce the organic materials; (b) provide an adequate airflow to maintain an excess oxygen supply; (c) remove the residue or ash; and (d) control particulate emissions. Airflow may be by natural or forced draft.

There are two types of air-suspended combustion systems: (a) those which suspend the burning fuel in the flue-gas stream in the combustion enclosure; and (b) those which suspend the fuel in the gas stream and in another medium, called the fluidized bed. Advantages of flue-gas stream suspension include a more rapid response to automatic control, an initial cost savings, and the ability to complete combustion with a much smaller percentage of excess air in the reactor.

Fluidized-bed suspension burning systems have the advantage of the flue-gas stream suspension, plus several others resulting from the fact that the fluidized-bed, usually a sand-like material, acts as a "thermal flywheel" of large capacity. Thus, feedstocks of varying densities, particle sizes, and moisture contents with variable or even intermittent feed rates can be handled easily with little or no particulate emissions. Also, savings of auxiliary fuel for preheating on the next startup are appreciable in the case of intermittent operation. Thus, the fluidized-bed system is suited particularly well to agricultural biomass feedstocks. Disadvantages are that a slightly higher level of operational expertise is required and the initial system cost is greater (74).

Gasification

Gasification is the process of turning solid biomass into a gas suitable for use as a fuel or for chemical synthesis. When the oxygen supply is restricted, incomplete combustion occurs releasing combustible gases such as carbon monoxide, hydrogen and methane. A solid residue or char remains (74).

The types of reactors suitable for gasification include updraft, downdraft, fluidized-bed, and entrained flow reactors. These are described in detail in the recent OTA report mentioned earlier (13). The entrained-flow reactor is the fastest of these four, but has the disadvantaged of requiring a finely ground feedstock and the fuel gas contains considerable ash. If the ash is cleaned from the gas by wet scrubbing, then the waste water may contain toxic compounds such as phenol.

Fluidized-ged reactors have the advantages described earlier in the direct combustion section plus they are much faster than the updraft of downdraft gasifiers. Properly designed fluidized-bed reactors can be operated in either the combustion or gasification mode.

The updraft and downdraft gasifiers are the slowest, but they also are the simplest to construct. In the updraft reactor, hot gases flow counter to the feedstock. Part of the fuel stock is pyrolyzed and the resulting gas has a high tar content. In the downdraft system, pyrolsis products are broken down as they pass through the reactor zone before combining with the exiting gases. Since downdraft reactors have the potential to eliminate tar from gas, they may be better suited for burning crop residues as a fuel source.

The ideal gasifier would be simple to construct and operate, produce no ash in the fuel gas, completely gasify the feedstock (producing no char or tar), accept a wide range of feedstock sizes and moisture contents, and gasify the feedstock rapidly. The downdraft and fluidized-bed gasifiers appear to be the most favorable types, but further development of all types is required before a clear choice can be made. It is likely that different gasifier types will prove superior for different feedstocks and applications (13). Much research and development are underway in this area.

Experience in Europe during the 1930s and 1940s indicates that gasifiers can be used to fuel internal combustion engines (77). Results of this experience with automobile and truck engines indicated a significantly greater amount of downtime for maintenance and a 30 percent reduction in power when operating on gas. Even though the gasifiers would be unlikely for automobiles today except in extreme fuel shortages, the potential exists to use gasifiers to fuel especially designed internal combustion engines for irrigation water pumping or electrical generation. The problem of excess downtime for maintenance would have to be solved, however.

The principal difference between gasifying for close-coupled boiler operation and process heat and for internal combustion engines is that the latter application requires that the gas be cooled before entering the engine and requires particularly low tar and ash content. The cooling is required to enable sufficient gas to be drawn into the cylinder to fuel the engine and prevent misfiring. The gas cleanup system is required to prevent fouling or excessive wear in the engine (13).

Gasifiers could be used as the sole fuel for gasoline engines or together with reduced quantities of diesel fuel in diesel engines (by replacing the air intake with an air-fuel gas mixture). The energy lost in cooling the gas and removing the tar and the added cost of the cooling equipment are likely to more than double the gas costs over that for close-coupled gasifiers (13). The gas is generally not competitive today with use of electricity, gasoline, and diesel fuel for irrigation pumping, but with increasing energy prices may be competitive with natural gas in the near future (13). Improvements will have to be made in gasifier efficiency and reliability to improve the applicability of gasifiers to internal combustion engines for crop irrigation, however.

Pyrolysis

Pyrolysis is the transformation of an organic material into another form by heating in the absence of air. The principal products of pyrolysis are gases, oils and char (74). If heat is applied slowly under pressure and in the presence of a catalyst, a pyrolytic oil can be produced. The pressure suppresses gas formation and the catalyst aids the formation of the oil. Rapid heating and cooling can also produce pyrolytic oils. Several pyrolitic processes are under study currently with mixed results (13). At present, the costs of producing pyrolytic oils appear to be very high in relation to air gasifiers and the efficiency of using the biomass feedstocks in this way is considerably lower than with gasification. Problems with current systems for producing pyrolytic oils from biomass feedstock include excessive tar and char production, costs, and corrosiveness of the product.

Methane Production by Anaerobic Digestion of Animal Wastes

Anaerobic digestion is a conversion process for wet biomass such as animal manure, municipal sewage and certain industrial wastes (74). In this process, various kinds of bacteria consume the wet biomass in an airtight container called a digester.

This biological process if as follows:

$$\begin{matrix}\text{Organic}\\\text{matter}\end{matrix} + \text{Bacteria} + \text{Water} \longrightarrow \text{Methane} + \begin{matrix}\text{Carbon}\\\text{dioxide}\end{matrix} + \begin{matrix}\text{Hydrogen}\\\text{sulfide}\end{matrix} + \begin{matrix}\text{Stabilized}\\\text{Effluent}\end{matrix}$$

The resulting biogas is 60 to 70 percent methane with most of the remainder being carbon dioxide (CO_2). Methane-forming bacteria are sensitive to environmental conditions in the digester such as pH (6.6 to 7.6 optimal), temperature (35°C and 54°C are two preferred levels), and carbon/nitrogen ratio (30 to 1 optimal) (74). The bacteria may be present in the original material when charged (as in the case of animal manure) or may be placed in the digester when it is initially charged. The gas has the heat value of its methane component and can be used directly as a heat fuel or in internal combustion engines (13).

The anaerobic digestion process is especially well adapted to slurry-type wastes and has environmental benefits in the form of treating wastes to reduce pollution hazards and to reduce odor nuisances. Furthermore, an advantage results because the residual from the digestion process can be returned to the land, either directly as a fertilizer or possibly after refeeding to animals, to help maintain nitrogen and organic levels of soil. Other biomass energy conversion processes discussed to this point destroy most of the input material and the residues have little fertilizer or potential animal feed value (13).

Basic Process

There is much yet to be learned about the bacteria and exact biochemical processes involved in anaerobic digestion. However, the basic process consists of three steps (13): (a) decomposition (hydrolysis) of the wet biomass to decompose it to usable-sized molecules such as sugar, (b) conversion of the decomposed matter to organic acids, and (c) conversion of the acids to methane. Accomplishing these steps involves at least two different types of bacteria.

The rate at which the biogas forms depends on the environmental conditions mentioned earlier but also on the nature of the material to be digested. Sewage sludge and animal manure produce biogas much faster than cellulosic materials such as crop residues. Disturbances of the digester system, changes in temperature, feedstock composition, toxins, etc., can lead to buildup of acids that inhibit the methane-producing bacteria. Generally, anaerobic digestion systems work best when a constant temperature and a uniform feedstock are maintained.

When a digester is started, the bacterial composition is seldom at the optimum. If, however, the biomass feedstock and operating conditions are held constant, a process of natural selection takes place until the bacteria best able to metabolize the feedstock dominate. Biogas production begins within a day or so, but complete stabilization may take much longer, sometimes months.

Numerous kinds of anaerobic bacteria have been tried, though the process is basically one of hit and miss (13). It is difficult to assess the potential for improvement at this time. Experience with biogas such as in India leads some to conclude that the benefits of the biogas schemes have been over-estimated (64). Too often the benefits are estimated on the basis of ideal estimates rather than data collected under operating conditions.

Biogas yields vary widely depending on feedstock and operating conditions. The optimum conditions for biogas yields have to be determined separately for each feedstock or combination of feedstocks.

Reactor Types

There are numerous possible designs for anaerobic digesters, depending on the feedstock, the availability of cheap labor, and the purpose of the digestion. Design parameters include continuous versus batch processes, mixed versus unmixed reactors, variable versus fixed feed rates, and other features. In Chapter 9 of the Office of Technology Assessment report on energy from biological processes, ten different anaerobic digestion systems are described in detail with excellent supporting drawings (13). Applications and inputs, scale, stage of development, advantages and disadvantages are presented for each system. This material will not be repeated here. It is worthy of note, however, that variations of these systems are currently used in several developing countries, particularly India and Korea (75).

Energy Production

Although many factors affect output, Table 7 illustrates the gas production rate and energy output for various feedstocks. To translate energy output into common language, the daily manure from a single 630-kg dairy cow could produce 1.8 m^3 of biogas or the equivalent of 1.25 liters of gasoline.

Table 7. Approximate Daily Production and Heat Values for Biogas.

Livestock 454 kg Body Weight	Approximate Biogas Production m^3/day	Approximate[1/] Heat Value, MJ	Approximate Equivalents			
			Gasoline L [2/]	Diesel Fuel L [2/]	Natural Gas m^3 [2/]	Propane kg [2/]
Beef	0.85	19	0.57	0.53	0.51	0.4
Dairy	1.3	29	0.87	0.76	0.76	0.6
Poultry broilers	2.6	58.3	1.7	1.6	1.6	1.2
Poultry layers	2.0	45.6	1.4	1.2	1.2	1.0
Swine	0.82	18.4	0.57	0.49	0.48	0.4

1/ Assumes biogas containing 60 percent methane or heating value of 22 MJ/m^3

2/ Heating values: gasoline, 3.6 MJ/L; diesel fuel, 37.1 MJ/L; natural gas, 37 MJ/m^3; propane, 49 MJ/kg.

Biogas Utilization

Biogas cannot be liquified at any pressure at commonly occurring temperatures, seriously limiting its use in mobile vehicles. It is better suited for use in high compression (13-14:1) stationary engines designed or modified to operate on methane. In biogas-powered stationary engines, waste heat can be recirculated in the digester coil and gas can be used as it is produced without a compressor storage unit. Full engine power is realized only if carbon dioxide is removed from the biogas mixture to increase the energy content of the gas. Longer engine life is attained if hydrogen sulfide is also eliminated from the gas before use.

Methane-driven stationary engines have a variety of uses but two likely ones are for pumping irrigation water or for electrical generation. Since biogas is comprised mostly of methane, it can also replace natural gas for heating.

Use of Sludge

Digester waste or sludge is an excellent fertilizer containing all the potassium and phosphorus and up to 99 percent of the nitrogen originally in the manure. In addition, trace elements such as boron, calcium, iron, magnesium, sulphur, and zinc remain unchanged.

Sludge could also be used in livestock rations if mixed with molasses, grains and roughage. Water must be removed by centrifuge to concentrate the protein and some of the protein dissolved in the water is lost.

Ethanol Production from Agricultural Crops

Alternate renewable energy technologies for biomass conversion considered up to this point are directed toward utilization of plant or animal residues, not the direct food product. The primary feedstocks for ethanol production (for which viable technology is available today) are either starch or sugar crops which can be used directly for food in many cases. Thus, the potential food/fuel conflict could become a serious consideration, particularly in developing countries. Also, much controversy surrounds the energy balance, i.e., the concern that the energy input required to produce ethanol may be equal to or greater than the energy value of the alcohol fuel produced (13, 23, 45, 71, 74). Nonetheless, ethanol from biomass offers considerable promise for application in developed countries and perhaps developing countries because it represents a viable liquid fuel which is renewable and which can be used to meet a wide variety of both stationary and mobile energy applications. Regarding the energy balance in producing ethanol, it is particularly important when fossil fuel is used to provide the energy for fermentation and distillation. When low-grade residues are available, they may be used with the technologies described earlier to provide the process heat.

Much has been written and spoken in the last few years about alcohol fuel from biomass. Here, the basic process for ethanol production from starch and sugar feedstocks will be presented, some considerations regarding small-scale (on-farm) production will be given, progress in the conversion technology for cellulosis feedstocks will be discussed, and finally brief consideration will be given to the use of ethanol in engines.

Basic Process

All processes for the production of ethanol through fermentation consist of four basic steps: (a) the feedstock is treated to produce a sugar solution; (b) the sugar is then converted to ethanol and carbon dioxide by yeast or bacteria in a process called fermentation; (c) the ethanol is removed from the fermented solution by a distillation which yields a solution of ethanol and water that cannot exceed 95.6 percent ethanol at normal pressures due to the physical properties of the ethanol-water mixture; and (d) if pure ethanol is desired, the water is removed by further distillation in the presence of chemicals (13).

Ethanol can be produced from starch and sugar feedstocks with commercially available technology. The main distinctions among the processes using different feedstocks are the differences in the pretreatment steps. Sugar crops such as sugarcane, sweet sorghum, and sugar beets yield sugar directly which can go into the fermentation process, but the sugar often must be concentrated to a syrup or the sugar will be destroyed by bacteria. Starch feedstocks such as corn and other grains require an extra step prior to fermentation, that being a rather mild treatment with enzymes or acid and then cooking to reduce the starch to sugar.

Regarding energy consumption in the conversion process, the sugar feedstocks would at first glance seem to have an advantage because the energy needed to reduce the starch to sugar is not required. However, this is not necessarily the case because processes for extracting sugar from the feedstock and concentration to syrup require a lot of energy.

Regarding byproducts and their potential utilization, the stillage from the starch feedstock can be reduced in moisture content and utilized effectively as livestock feed since the feed value of the original product has not been reduced. The value of the byproduct from the sugar feedstock is of questionable value and may pose a definite disposal problem.

If sugar crops having little food value such as sweet sorghum and cull fruits and vegetables are used as feedstocks, then the matter of the food/fuel dilemma is less of a problem. However, these products are perishable and to be most economical, an alcohol plant must operate year round thus requiring a feedstock that can be stored, such as the starchy grains.

Small-scale Systems

Considerable interest has been expressed in individual farmers or farm cooperatives producing ethanol. A number of factors, however, could limit prospects of such production.

A farmer must consider a number of site-specific factors before deciding to invest in an on-farm unit. Some of the more important of these are (74):

> Investment - How much does the system and related equipment cost?
>
> Use of the ethanol - Will the ethanol be used on farm or sold? What engine modifications are necessary? Will the farmer be dependent on a single buyer?
>
> Labor - Does the farmer have access to low cost, qualified labor, or is it better to make a large investment for an automated system?
>
> Skill - Although ethanol can be produced easily, the process yield--and thus the cost--as well as the safety of the operator can depend critically on the skill of the operator.
>
> Equipment lifetime - Less expensive systems may be constructed of materials that are destroyed by rust and corrosion after a few years' operation.
>
> Fuel for system operation - Does the farmer have access to wood or crop residues and combustion equipment that can use these fuels? Can reliable, inexpensive solar stills be constructed for the distillation step? If oil or natural gas is used, would it be less expensive to use this fuel directly?
>
> Byproduct - Can the farmer use the wet byproduct on the farm? Will this complicate the feeding operations or make the animal operation dependent on an unreliable alcohol plant? What will drying equipment cost and how much energy will it consume?
>
> Water - Does the farmer have access to sufficient water for the alcohol plant?

As a profitable venture in absence of large subsidies, small-scale, on-farm alcohol production is, at best, marginal with current technology.

Cellulosic Feedstocks

The feedstocks with the largest long-term potential for ethanol production -- both in terms of absolute quantity of ethanol and in terms of the quantity of ethanol per acre of cultivated land -- are the cellulose-containing feedstocks (74). These include wood, crop residues, and grasses, as well as the paper fraction of municipal solid waste.

A major research and development effort is underway in the United States to convert cellulosic materials to sugars by acid or enzyme hydrolysis and then to alcohol through the aforementioned processes. Although major breakthroughs must first be made, successful commercialization of cellulosic conversion to alcohol would greatly expand the feedstock base, make alcohol production more independent of the supply of food and feed grains, and thus make the alcohol fuel potentially more attractive.

Ethanol Use in Engines

Ethanol has a higher octane rating and is a cleaner burning fuel than gasoline. Thus, it is an effective fuel in engines. The amount of pure ethanol in the product (ethanol proof) ultimately determines how it can be used. No engine modifications are necessary when "gasohol," a mixture of 10 percent pure ethanol and 90 percent gasoline, is used. Also, since there is only a 3 percent difference in heating values for gasoline and gasohol, only a small difference in power output and fuel efficiency is expected (13,37,74).

Lower proof ethanol, such as can be made in a small-scale alcohol plant, can be burned straight in suitably modified spark ignition (gasoline) engines. The necessary engine modifications are related to the following combustion characteristics of ethanol relative to gasoline: (a) requires 20 to 40 percent less air for combustion, (b) has several times the cooling effect during evaporation, (c) has twice the flame speed, (d) has a higher octane number, and (e) boils at 78.3°C. Gird, in his report on utilization of ethanol fuel, delineates appropriate engine modifications to accommodate these differences (37).

Ethanol is not well suited for use in compression ignition (diesel) engines and thus cannot be burned straight. Use of straight ethanol would require major design changes in engines and fuel systems to assure proper ignition of the ethanol and lubrication of the injection system.

There are two other approaches to burning ethanol in a diesel engine. Pure ethanol may be mixed with diesel fuel and injected in the normal way, but modification of the engine is required. Another approach is to introduce ethanol into the intake air. The remainder of the fuel (diesel oil) would be injected by the normal injection system. This method is commonly called fumigation and Gird outlines needed engine modifications and precautions when using this method (37).

Ethanol is a very volatile fuel. Therefore, safety is most important in production, storage and use of ethanol. One example is that gaskets and seals in the engine fuel system that were designed for gasoline or diesel fuel may be deteriorated rapidly by ethanol. Gird gives many additional safety considerations for ethanol production, storage and use (37).

Plant Oils as a Diesel-Fuel Substitute

Agriculture throughout the world is moving more and more toward the use of diesel engines for providing mobile and stationary power. Shortcomings of alcohol as a diesel-fuel substitute were discussed in the previous section. Plant oils, such as peanut oil, soybean oil, and sunflower oil, are a renewable biomass source which offers considerable promise as a diesel fuel substitute or extender.

Several plant oils have the energy content and thermal ignition characteristics (cetane number) to make them potential candidates to serve as a diesel fuel. The energy content of Number 2 diesel fuel, several plant oils, and ethanol are:

Fuel	Kcal/liter
No. 2 diesel	9,320
Peanut oil	8,860
Corn oil	8,790
Cottonseed oil	8,720
Soybean oil	8,660
Sunflower oil	8,520
Ethanol	5,590

Thus, the energy content of plant oils is approximately 90 percent that of No. 2 diesel fuel whereas the figure for ethanol is about 60 percent.

A number of short-term tests using plant oils as a diesel fuel have shown that diesel engines can operate without modification on plant oils. The long-term effect on engines of using these fuels is not presently known nor have the difficulties to be expected under a wide range of operating conditions been documented. This points to the fact that operational problems may be expected until all these potential difficulties are solved.

The potential yield of oil from various crops is relatively high. For example, rainfed peanuts under good conditions may yield 2,800 Kgs/hectare which can be converted into approximately 935 liters per hectare of peanut oil for use as a diesel fuel.

The energy balance for producing plant oils is much more favorable than that for ethanol production. For example, defining the energy balance as the ratio of total energy in the fuel to gross energy input (agricultural production and processing), the energy balance ratio for sunflower oil can be over 6:1.

Plant oils have the same shortcoming as ethanol in that they use food crops for production of fuel, hence the potential food/fuel conflict is again a factor to be considered. However, the plant oil byproduct is the seed meal which has value as a fertilizer, as a protein supplement for animal feeds, and possibly as a human food supplement particularly in any developing countries where protein dietary supplements are vitally needed.

The technology for extracting plant oils is a simple mechanical process adaptable to a low-technology operation. The oil is obtained by crushing the seed in a screw press operation in which the oil is literally squeezed out of the seed. This process is different from the solvent extraction process used in large commercial oilseed processing plants. As an example, for sunflowers, the screw press or expeller operation involved the following steps (44):

1.	Whole Seed	The seed needs to be cleaned before any further operation. Any stones or metal pieces will damage the expeller. It may also be advantageous to size the seed prior to pressing.
2.	Dehuller	It may be desirable to remove the hulls to reduce the fiber content and increase the protein content of the meal.
3.	Roller Mill	Some types of seed breakage may be advisable. Whole seed can be used but efficiencies of oil recovery are lower.
4.	Cooker	Some means of heating the seed prior to pressing is needed to obtain the maximum oil recovery.
5.	Screw Press	The press separates the oil from the meal. The meal will still contain some oil, however, The amount will vary from 7 to 15 percent on a dry weight basis.
6.	Filter	The oil needs to be filtered to remove seed particles.
7.	Crude Oil	The oil may need additional processing to remove phosphatides and waxes. The exact amount remains to be determined.

As with most of the alternate renewable energy resources, several important research and development questions must be addressed and answered for plant oils. These questions include: (a) the long-term effects of plant oil fuels on engine performance; (b) the minimum degree of processing of plant oils required to produce a suitable fuel; (c) optimal blending rates (if required) of plant oils with diesel fuel; (d) improved techniques for small- and large-scale production of plant oil fuel; and (e) economic considerations.

Plant oils and ethanol are complementary in that the plant oils are good diesel-fuel substitutes and ethanol is a good gasoline substitute or extender. Based on the indicated plant oil potential as a fuel, major research and development efforts seem well justified.

Direct Use of Solar Power

Solar technologies are another possible source of renewable energy for developing countries. Solar energy is an environmentally clean source of power but the energy is not concentrated and capital costs to utilize it are very high currently. Water heating by flat plate collectors is the solar technology most ready -- technically, economically and commercially -- for widespread application (12). Some developing countries have begun to manufacture their own solar water heaters, and many others could do so. Flat plate collectors can be an economic source of hot water for residences and industry; they can also provide heat for drying crops and certain other agricultural uses, but they are not well suited to providing energy for irrigation pump engines. The thermodynamic efficiency of converting low differential temperature heat sources into mechanical energy is very low.

Photovoltaic cells, which convert solar energy directly into electricity, appear technically feasible to applications in developing countries because they promise to be long-lived and relatively trouble-free in operation. But while the cost of photovoltaic energy is falling, it is still very high (approximately $2/Kwh). It is not now commercially viable except where relatively small amounts of power are needed in remote locations. The use of photovoltaic cells to meet power needs for low lift, small farm irrigation and village water supply pumping is being tested in a number of countries (12). In our judgment, this technology is a long way from being practical for irrigation applications in developing countries.

A proposed irrigation system powered by solar energy is reported in a recent publication of the Solar Energy Research Institute of the U.S. Department of Energy (46). This approach involved the following technologies:

photovoltaic cells,
shallow solar ponds driving organic Rankine cycle turbines, and
collectors with engines driving a mechanical pump.

These systems have been proposed for the Southwestern United States and Israel. It is speculated that these photovoltaic cell-powered irrigation systems might become cost effective with photovolaic cell array prices of $500/peak kilowatt, perhaps sometime between 1985 and 1990 depending on the fuel cost escalation rate (46).

Solar ponds have a potential of being a low-cost solar collector with inherent thermal storage. Shallow solar ponds now being studied are essentially large plastic bags filled with saline water that collect solar energy. When they are used in conjunction with a nighttime thermal pool, the energy drives organic Rankine cycle engines, which in turn power the irrigation pumps. The Solar Energy Research Institute report provides a detailed description of this proposed solar energy conversion technology (46). It could under good conditions be a solution for large-scale electric power production in areas of the world where water, salt and sun are available in abundance. This solar technology provides the best possibility to date for use of solar energy for irrigation, but the capital cost is expected to be quite large.

Newkirk recently published two survey reports on solar technology applications for irrigation pumping systems (61,62). Both are state-of-the-art literature reviews including information on world patents that have been granted. It was acknowledged that much of the information provided was tentative, rapidly changing, and highly variable in time and place. The reader was advised that the information should only be used as a guide.

The results reported in the summaries of the 60 references of on-going work included reports of thermal systems, thermoelectric systems and photovoltaic systems. For the strait thermal systems some encourageing reports are presented, although in most cases the capacities of the pumps are small, often represented as a few cubic meters per hour. The power output relates to the size of the collector area and if very large collectors are used, sizeable pumping systems are possible. Systems with large arrays of sun-tracking energy concentrating mirrors can provide energy to pump large quantities of water. For example, a large installation in Arizona intercepts 564 square meters of sunlight in parabolic tracking solar collectors and is capable of generating 3700 KW (50 hp) of power at peak operation (56).

For one 9.5 hour day the system pumped 21,000 m^3 of water. However, the capital cost of this experimental system is very high and it is a long way from being suitable for developing countries.

A measure of the current economic suitability of direct solar energy for pumping irrigation water comes from life cycle cost analyses of some of these systems to determine their economic feasibility. When systems were used only to pump water, the life cycle cost of solar systems ranged from 3 to 1.7 times as great as conventional electrical systems for projected start up dates of 1980 and 1990 (52). This was for southern Arizona in the United States -- an area with great quantities of solar energy. Therefore, even for an installation projected for 10 years hence the life cycle cost is expected to be almost twice that of a conventional system.

Chadwick experimented with three models of low-head solar powered irrigation pumps (22). His simple pumps would work for lifts of 2 to 3 meters He postulated that the pumps might be suitable for some low head applications if the capital equipment cost is sufficiently low and free solar energy is readily available. Pumping efficiencies of one percent or less were measured and one experimental model pumped 6 liters per minute at 2.5 meters lift. Such a pump would require 115 days to pump 1000 cubic meters of water, enough to apply a gross 10 centimeters of water to only one hectare.

Using Chadwick's estimate of 50 percent solar collector efficiency and one percent pump efficiency, the useful energy from each square meter of intercepted solar energy can theoretically lift 0.6 $meters^3$/hr a height of 15 meters. To lift enough water to irrigate one hectare with 10 centimeters gross application at one-week intervals would require about 150 square meters of collectors if the pump operated eight hours per day (the approximate amount of time the sun would be high enough to provide the necessary radiant energy of one $kilowatt/meter^2$). Chadwick's designs, however, are suitable only for low head applications (2 to 3 meters) and could not be used to lift water 15 meters.

A comprehensive state-of-the-art assessment of the feasibility of small-scale solar powered pumping systems is contained in a 1979 report prepared with support of the United Nations Development Program (UNDP) and the World Bank (39). The feasibility of providing small scale solar powered pumping systems for irrigating farms of about one hectare size when pumping from a depth of about 5 meters is reviewed.

To irrigate a one hectare farm with one meter gross irrigation per year requires that 10,000 $meters^3$ of water be pumped. The World Bank and UNDP considered that solar powered pumping systems will ultimately need to deliver water at a cost not exceeding U.S. \$0.05/$meter^3$ (1979 prices) to be economically attractive (39). This corresponds to an annual irrigation water cost of \$500 for a one hectare farm. Therefore, the total annual operating cost of the solar powered pumping system should not exceed U.S. \$500 if it is to be viewed as potentially competitive. Assuming 9 percent of this annual cost (\$45) is for maintenance (a maintenance charge that may be too low) and 91 percent for amortizing the purchase, the maximum purchase price of the solar pumping unit for this one hectare farm is determined (39). Table 8 gives the maximum purchase price for the complete solar pumping system using different interest rates and amortization periods.

Table 8. Maximum Capital Cost of Solar Irrigation Pumping System for Various Assumed Interest Rates and Amortization Periods

Amortization Period, Years	Interest Rate, Percent			
	4	7	10	14
5	2,022	1,864	1,723	1,563
10	3,700	3,204	2,808	2,370
15	5,055	4,136	3,446	2,791
20	6,149	4,840	3,888	3,013

It would indeed be fortunate if the life of solar powered irrigation equipment proved to exceed 10 years. Assuming the interest rates are 10 percent, then the maximum investment in the solar energy pumping system cannot exceed \$2,808 if the cost of irrigation water is to be kept to the postulated target of \$0.05/meter^3 or less and the amortization period is 10 years.

At present, it cannot be stated with any certainty whether the solar photovoltaic pumping system or one of the possible solar thermal pumping systems (Rankine organic vapor engine, Rankine steam engine or Stirling engine) has an advantage over the others. However, it appears that the solar photovoltaic system may have the best potential because of possible breakthroughs in reduction in cost and improvement in efficiency and dependability of the photovoltaic cell arrays. However, the photovoltaic system may not be so amenable to local manufacturers in developing countries, a disadvantage.

The conclusion that must be reached is that solar energy technologies can provide power for pumping irrigation water. However, as yet the economic feasibility must await more research and development before it can be proposed for any widespread use in developing countries. Moreover, the technologies are still quite complex and likely beyond that which can reasonably be expected to be successful in most developing country settings under current conditions.

Wind Power

Windmills, generating power from wind or indirectly pumping water into elevated storage, were among the first prime movers that replaced man as a source of power. The earliest recorded use is attributed to Persians in approximately 600 A.D., introduced into Europe in the 12th Century as a primary power source and during the 19th Century produced over 25 percent of the nontransportation energy in the United States (17). This inexhaustible, though site specific and intermittent, source of energy has the advantage of being pollution free.

Since 1972, wind energy technology development has experienced its most rapid growth in history. Worldwide experiments with wind turbine generators are numerous with emphasis on developing both small and large utility interconnected generators (17).

The useable global wind energy potential is estimated to be 3900 quads/yr (1 quad = 10^{15}Btu = 2.52 x 10^{14}Kcal) or more than 39 times the usable global energy potential for the combined renewable energy sources of hydropower, geothermal heat, and tidal energy. In the United States, it is estimated that 2 million 1,000-Kw wind turbine generators could be installed before environmental influences of the machines become important. These generators could produce 50 quads of electricity annually. Thus, wind energy conversion systems could produce a significant amount of electrical energy.

An analysis of 1979 wind turbine generator costs shows that large generators in excess of 300 Kw are not economically competitive even in high wind sites. Commercially available wind turbine generators smaller than 40 Kw may have economic applications if located at sites with average winds greater than 19 Km/hr, if tax benefits or other subsidies are provided (17). However, wind turbine generators in the 40 Kw to 250 Kw size range have demonstrated economic feasibility; they could power irrigation pumps or provide rural electric cooperatives, municipal utilities, large farms and small businesses with electricity at 3 to 6¢/Kwh at sites with average winds of 19 km/hr or greater. Wind turbine generator costs should decrease further in the 1980s as economics of mass production are realized.

In summary, windmills can be used at suitable sites with consistent winds of 19 km/hr or more in developing countries to lift water for irrigation. If winds are intermittently sufficient and a suitable water storage site is available, windmills can lift water to elevation for storage from where it can flow by gravity to meet irrigation needs. Wind turbines also can be used to generate electric power for pumping or assisting in pumping irrigation water However, there are many areas of the world where wind energy is not reliably available with sufficient velocity. The key words are "suitable sites;" winds must be relatively high and steady. The intermittent nature of winds in many locations is an inherent disadvantage of wind power. A firm technical basis exists for windpower projects, and they appear to be economically attractive for suitable sites, but there has been little recent experience with them and much more exploration of sites is needed to assess their potential role (12).

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Chapter IV

ADVANTAGES AND SHORTCOMINGS OF ALTERNATE RENEWABLE ENERGY SOURCES FOR IRRIGATION IN DEVELOPING COUNTRIES

In the previous chapter, various alternative renewable energy sources which may have application for irrigation in developing countries were presented and discussed. At the outset in this chapter, it must be stated that, as of this time, none of these alternatives is economically competitive with the fossil fuels (oil, gas, coal) directly or with electricity generated from these fossil fuels or with nuclear power or with hydroelectric power where it is available. This is particularly true for an operation such as the irrigation of agricultural crops where the amount of energy required for pumping can be so very great.

It is also a fact, unfortunately, that the world supply of fossil fuels is finite and that the worldwide demand for these precious resources will continue to grow. Thus, future price increases for petroleum products are inevitable. It is also quite likely that some of the alternative renewable energy sources will become economically competitive at some point in the future as energy prices continue to increase.

Another fact is that the extension of low-energy techniques now commonly used in developing countries -- the man or woman with only a hoe or with bullock and plough and ox-cart transportation -- will not produce the food supplies needed for rapidly growing urban populations, often far removed from areas of agricultural production (75). Poor countries need as much energy as they can get, as cheaply as possible.

Revelle in his analysis of energy use in rural India points out that a considerable increase in energy use will be necessary to meet future food needs -- primarily for irrigation, chemical fertilizers and additional draught power for cultivation (68). The climate and water supply permit two crops per year on most of India's arable land, but this will be possible only with greatly expanded irrigation and fertilization. The India Irrigation Commission estimates that for full irrigation development about 46 million net hectare-meters of water should be pumped annually from wells, requiring at least 10^{14} kilocalories of fuel energy -- four times the bullock, diesel and electric energy now being used. Large additional increases in energy are needed also for fertilizers and cultivation.

Revelle concludes his study as follows (68):

> The man and women of rural India are tied to poverty and misery because they use too little energy and use if inefficiently, and nearly all they use is secured by their own physical efforts. A transformation of rural India society could be brought about by increasing quantity and improving the technology of energy use.

This conclusion is applicable to virtually all the non-oil-producing developing countries in the world. Institutional constraints such as landlord-tenant relations, inequity of educational opportunities, lack of coherent energy resource plans with research and development efforts and appropriate extension delivery systems and political considerations must be overcome to permit development of the needed energy resources (75).

The developing world is, in many instances, amply endowed with solar energy and has considerable potential for biomass resources. These resources are particularly well suited to helping meet the widespread need for small, decentralized sources of energy where, because of lack of conventional energy supplies, renewable sources could prove economical sooner than in the industrialized countries (12). However, it must be stressed that the economics of developing countries renewable energy resources for pumping irrigation water are dependent on many yet unproven factors.

The remainder of this chapter will provide an evaluation of the alternate renewable energy sources for irrigation in developing countries presented in Chapter III. The following parameters are considered: costs, dependability and risk factors, state of technology, suitability of the technology for developing country conditions, supply or raw materials and food/fuel competition considerations.

Costs

Current literature abounds with economic analyses of alternative fuels. Unfortunately, it is very difficult to generalize about the economic feasibility of alternate fuels. Costs of fuel production from all alternate renewable energy sources are extremely site-specific. The economics of biomass fuels depend heavily on feedstock cost and availability, end use, transport distances of feedstock, and a host of other factors (13). Solar and wind power costs are also very site-specific, depending on abundance of the solar or wind resources.

Given that solar, wind and biomass resources are available in abundance, rankings will be made regarding energy production costs based on presently available data and currently available technology (13,17,46,74). These rankings, in terms of the likelihood that a technology will be suitable for developing countries show wind to have the lowest cost and direct solar energy the highest and are:

1. Wind (40-250 Kw size range)
2. Biomass (all technologies)
3. Direct solar energy.

Within biomass, the breakdown is as follows:

1. Direct combustion
2. Gasification
3. Methane production
4. Plant oils
5. Ethanol production.

Pyrolysis is not technologically developed to the extent that a meaningful ranking can be made. Direct solar conversion with current technology is much more expensive (5 to 10 times) than any of the other conversion technologies. Research and development breakthroughs could, of course, change the economic picture and hopefully they will. It should be reiterated, however, that in general none of these technologies compete well with present conventional energy sources (fossil fuels, electricity, nuclear and hydropower). An exception might be wind energy at ideal sites of consistent winds of greater than 19 km/hr.

Dependability and Risk Factors

For irrigation purposes, it is most important that the source of power be dependable because the entire crop can be lost or greatly damaged if water is not applied at certain growth stages when it is critically needed. Both solar and wind power depend on intermittent sources of energy, except in very few locations, and it is important that some energy storage mechanism be a part of the technology for each of these if they are to be sole sources of power for irrigation. Local availability of maintenance and replacement parts in case of equipment breakdown is also a very important consideration.

State of Technology

Major research and development efforts are continuing and increasing for all the alternate energy technologies. The wind conversion and direct combustion technologies are the most advanced at this time, followed by methane production, gasification, ethanol production, and solar. Plant oil extraction is a simple process, but not as much research and development effort has been made in this area using simple screw presses. The state of this technology could move ahead of the others rapidly with appropriate research and development emphasis, but much remains to be accomplished before the technology can be generally applied. Pyrolysis technology is the least developed of those discussed in this chapter.

Suitability of Technology for Developing Country Conditions

Highly sophisticated technology requiring highly skilled operators is not well suited to use for providing energy for irrigation in developing countries. Ideally, the equipment involved should be simple to operate, reliable and trouble-free, and have a long life. This is true also for applications of new technologies in developed countries, but it is critically important in developing countries. Regarding maintenance and repairs, it would be most desirable if the replacement parts could be fabricated locally and, in fact, local manufacture of the entire conversion system would be desirable.

Very few of the alternate energy technologies score well in terms of suitability for developing country conditions. Direct combustion, gasification, methane production, and windmills would rank highest on a "suitability" list, with plant oil extraction having great promise, but all still have problems to be solved. The "solar pond" technology coupled with photovoltaic cells and wind turbine generators are fairly complex and likely to remain very expensive. Ethanol production comes next on the list with pyrolysis being least suitable based on current technology.

Supply of Raw Materials and Competing Uses

Solar and wind energy sources, where abundantly available in nature, have a distinct advantage over biomass energy sources in that they have no competing uses. In most cases, there are alternate uses for biomass -- fuel is only one of these.

The basic purpose of agriculture is to produce food and fiber for humans. Thus, forms of biomass and fiber that constitute human diets or feed for animals ultimately consumed by humans must be reserved. If surpluses exist or more biomass can be grown, over and above the needs for human and animal diets, they may be considered for fuels. But if biomass is used for fuel, its impact on food prices and availability must be very carefully considered (13).

There is, undoubtedly, a tradeoff between socially desirable goals of low food prices and energy availability. Inadequate energy supplies for any segment of the food system could seriously affect food availability and price.

Many forms of biomass are not edible by humans and undesirable as animal feed or fiber. There are undoubtedly cases such as municipal solid wastes or food processing wastes where the biomass product is truly a "waste" and requires an expenditure to dispose of it. Without question, when such wastes exist, conversion to useful fuels should be explored. However, such wastes are to a large extent already recycled, burned for fuel, or otherwise consumed in developing countries pointing to the serious problem of supply of waste feedstock materials for producing fuels.

Many byproducts or residues have alternate uses and positive economic values associated with each use. Some crop residues must be returned to the soil for erosion control and maintenance of organic matter levels. Also, crop residues contain substantial quantities of plant nutrients which must be replaced if the residue is removed from the land.

Biomass is also used for structural material, bedding and a variety of miscellaneous uses. If biomass is to be used for fuel, its value as a fuel must compete with alternate uses, particularly food. Devoting agricultural land to biomass energy production will always be a critical issue in any food deficient nation.

In conclusion of this chapter, it is of fundamental importance in alternate renewable energy development that research and adaptation to local conditions be given high priority. Quoting the recent World Bank study on energy in the developing countries (12):

> The developing world, by no means uniquely, finds itself short of the expertise needed to evaluate and exploit its resources. There are important gaps in the developing countries' ability to select from and adapt to their needs technologies being studied and developed by the industrialized countries, and especially technologies whose greatest potential is in the developing countries. To fill these gaps, attention needs to be given to strengthening national research programs and to the possibility of organizing international programs of research on specific renewable energy technologies.

Chapter V

OVERALL ASSESSMENT OF ALTERNATE SYSTEMS

Three issues are of primary importance in looking at energy in irrigation in developing countries and formulating guiding principles for policy decisions. First, there must be a clear understanding of the magnitude of the total energy requirements in irrigation as well as the critical nature of timing of these energy demands. This includes appreciation of the relationships between irrigation and other production inputs such as fertilizer and good seeds so that the food production potential of the improved seed-water-fertilizer approach is not lost because of inadequate irrigation water at the time of critical need. If a crop fails because of lack of water, the investment in both money and energy for other production inputs is wasted. Second, the level of technology required for the on-farm irrigation system and any alternate energy approach must be carefully assessed so that systems do not fail because the technology and all of its potential problems were not understood. Finally, the economic factors must be carefully considered to assure that systems are not proposed which are well beyond the reasonable economic reach of farmers in developing countries.

Food Production Effectiveness

Chapter II provides data on the general magnitude of energy requirements for various types of irrigation systems with the water supplied from various sources. The surface irrigation systems require the least energy and are also the least expensive to construct. Therefore, when soil and topographic conditions permit the use of surface irrigation, and when the system is well designed and managed, it is the best choice from both energy and dollar cost considerations. Surface irrigation requires more labor than other systems, however. Also, field water losses are often quite large if the systems are poorly designed, constructed and managed.

The effectiveness of an irrigation system in producing food is closely related to its ability to provide water to the crop at the time needed. The daily water requirement of an annual crop will range from a small daily amount at planting and seedling emergence, increasing to a maximum when the crop reaches full growth and starts its flowering and fruit producing stages (26). The daily water requirement in the early stages is usually 20 percent or less of the maximum requirement. Therefore, the irrigation system should have the capability to provide irrigation water on demand at the time the crop needs it most. Failure to provide the irrigation during the critical time of crop flowering and fruiting can severely reduce yields, perhaps by 50 percent or more. Therefore, any failure of the irrigation system or its power source during the time of critical water need is especially damaging. The small photovoltaic solar pumping system with low capacity may have difficulty meeting peak crop water demands.

This brings up the question of dependability of the irrigation power source. Electric pumps are inherently very reliable except for periodic electric power supply failures.

Several reports point to the fact that power failure is not uncommon in developing countries and often poses a serious problem for farmers. Therefore, this matter requires careful consideration in determining the best energy supply for a particular situation.

The dependability of energy sources such as wind and sun require careful study. Windmills for many years have been used in pumping water. The use of wind energy will increase, but its potential for providing the sole energy source for irrigation must be thoroughly analyzed considering climatic records.

A word is in order regarding the problems of operating irrigation water supply reservoirs with hydroelectric power plants. Oftentimes the water released from the reservoir is controlled by the electricity demands on the hydroelectric plant rather than on the water demands for irrigation. The farmers are expected to use the water when provided rather than having it supplied when dictated by crop demands. While there is no simple solution to this age-old conflict, the timing of irrigation water needs should be considered insofar as possible.

Sensitivity of Systems to Operational Problems

There is danger of looking at the many possible problems with alternate renewable energy sources and concluding that the potential for technical problems is so great that nothing new should be tried. One can never foresee the future with sufficient clarity to be certain and this may lead to excessive caution. However, we know from past experience that the successful implementation of advanced technologies in developing countries requires that the state of the science should be sufficiently well developed to provide for relatively simple, trouble-free operations; otherwise the systems will continually be plagued by problems and perhaps abandoned. Poor farmers should not be expected to use systems which are experimental and without reasonably proven dependability. Therefore, we are forced to strike a balance between optimism toward alternate energy sources and the realism that for many the technical and economic problems are too great for their widespread successful application in the near future.

Some of the systems to provide alternate energy sources, such as from microbial decomposition in digesters producing biogas, are not new; yet they are still quite unreliable (64). Others, such as schemes for ethanol or plant oil production, are not dependent on the poorly understood processes of microbial systems and in the near future can be expected to become reliable processes. However, their success will be highly sensitive to the supply of the biomass feedstocks, the food/fuel conflict, and general economic factors. Also, the dependability of modified engines or those especially designed to use biomass fuels has not been thoroughly proven.

The technology or direct solar irrigation pumping remains complex. There are many potential technical problems with systems that use tracking solar collectors to concentrate energy and machines to convert this to mechanical or electrical power for pumps. The economics for these systems will improve in the years ahead but still will remain marginal for years to come.

Solar power through photovoltaics could progress rapidly if certain breakthroughs were to occur. Who would have imagined the progress which has been made in microelectronics and the development of simple inexpensive computers? Conceivably, with new techniques for continuous manufacture of silicon cells, similar progress might be made in photovoltaic devices or some other direct conversion of solar energy to electricity without moving parts or maintenance. If such occurs as a result of worldwide energy research, and has applications to help irrigation farmers, it will be a fortunate circumstance. However, the probability that simple, low maintenance and reliable photovoltaic powered pumps for irrigation will emerge suitable for widespread use in the near future, unfortunately, is not high. Also, the likelihood that photovoltaic cell arrays will be readily manufactured in developing countries is not great in the near future.

Regarding wind energy, the technology is relatively simple and reliable when dependable wind resources are available. As stated earlier, however, the availability of the necessary steady winds of 19 km/hr or more is not widespread. When the wind resource is available, it can provide a cheap energy source for pumping irrigation water and it should be carefully considered. There is a need to lower the cost of windmills through local production and this should be encouraged. Moreover, there will be times when wind energy can be used in conjunction with conventional irrigation pumping systems and this should also be considered. The system will be higher in cost since both the windmill and the conventional (diesel or electric) power source must be provided. The increased capital cost, however, may preclude this combination system for developing country operations for economic reasons.

Economic Factors

Any analysis of energy in irrigation in developing countries must stress the high capital cost of some of the systems that might be proposed. It is also important to keep the matter of human labor availability in perspective when considering irrigation in developing countries. If the technology of an irrigation system is too advanced and all the necessary supporting services are not available, the system should not be adopted without thorough justification. It is fortunate that surface irrigation, which effectively utilizes readily available labor, is the most energy efficient and also the least costly. Therefore, this method of applying irrigation water in the field has merit from a energy cost and dollar cost as well as labor point of view.

A word of caution is in order, however, when one looks at the cost of lifting water for irrigation. Much of the water lifted for very small irrigated farms is lifted with human power or animal power. The energy requirement for lifting irrigation water is so great, and the efficiency of animal and human powered devices is so low, that it is almost impossible to transfer enough animal or human physical energy to the devices and achieve any significant irrigation.

A study in Egypt considered the cost of lifting irrigation water using animal or human power versus electric or diesel pumps (11). The human power may be used to operate a shadouf or the tambour (Archimedes screw). Animal power may operate various types of sakias (water wheels) and in some cases tambours or other pumps.

Considering the capacities of two laborers on a tambour, working alternating shifts, two cows powering a sakia, also alternating the task, the practical capacities for lifting irrigation water were determined. In all cases the lifts possible were very low. Although the price for human labor was low, the cost of lifting of irrigation water by human power was about 3.7 times greater for human power than for a small 6.5 horsepower diesel pump. Cost using animal power was 1.6 times greater than for the diesel pump. Moreover, the potential for using animal and human power is limited to very small lifts and such is not the case for diesel or electric pumps.

Revelle performed calculations on the potential for using animal power and human power for irrigation in Chad (69). Even considering very expensive diesel fuel and very cheap human labor rates, the economic advantages of the mechanically or electrically powered system prevailed.

While it is true that little commercial energy (purchased energy) is required for lifting water with animal or human power, there is a sizeable energy commitment in human food and animal feed. Most importantly, the energy demands of irrigation pumping simply cannot be met by human strength and endurance and it is important to recognize that irrigated agriculture using any such system cannot be expected to advance beyond a low-yielding, primative state.

Chapter VI

ISSUES FOR GOVERNMENTAL POLICY CONSIDERATION

In discussing future sources of energy to solve energy problems, Dr. Edward A. Frieman, Director of Energy Research for the U.S. Department of Energy, stated that research to solve energy problems could conveniently be broken down into three stages -- near term for the next 15 years, mid-term from 15 to 40 years, and long term 40 years and beyond (35). He stressed the necessity of being realistic in terms of what research and technology can be expected to do in solving the energy problems. In looking at the next 10 to 15 years, Frieman emphasized the minimum time lag for development of and implementation of new technological breakthroughs. He stressed that governments can't do much to solve the near term problems except to promote conservation and press for research and development to solve the energy problems further into the future. He cautioned against any nation being misled into believing that there would be a simple technological solution to the energy problems. It seems quite unlikely that there will be simple solutions to the matter of short energy supplies and increasingly expensive energy.

In the near term, the next 15 years, the probability is not high that there will be a significant change in the source of energy supplies which support the approximately 100 million hectares of irrigation in the nations with developing market economies. There will be a considerable expansion of the experimental and pilot irrigation pumping systems using solar energy and other renewable, non-commercial energy sources. There are over sixty small photovoltaic pumping systems over the world (39). The water output of these solar pumps will likely continue to be small, of the order of 100 $meters^3$ per day or less, and of local importance but not of sufficient magnitude to have any significant worldwide impact. It is questionable if the solar pumping technology will have advanced within the next 15 years to make the systems economically justified under free-market conditions except in rare circumstances. However, this is speculation and the needed technical breakthroughs may occur more readily than anticipated. Hopefully, they will. The research and development work should continue worldwide.

Supplies of biomass energy sources in developing countries will continue in short supply in arid and semiarid nations. This coupled with the food/fuel conflict will hinder use of biomass fuels for irrigation on a widespread basis even though the technology will have advanced to make it practical in many settings. Wind energy will be utilized to a greater extent in locations where adequate wind resources are available and sufficiently dependable.

Although there will be numerous advances in the next 15 years related to irrigation, the action most likely to reduce commercial energy use in irrigation during this near term is conservation. Specific suggestions on ordering of priorities for conservation are given in a later section in this chapter under Specific Recommendations.

In the mid-term future, 15 to 40 years hence, there will likely be several practical solar powered pumping systems. The two of these which are judged to be the most probable are solar ponds, which could power relatively large irrigation pumps, and small solar photovoltaic systems. It is not far-fetched to think that the cost of solar photovoltaic arrays might have decreased in price to $150 to $250 (1980 dollars) per peak kilowatt by 1995, or soon thereafter, as the U.S. Department of Energy has speculated (39). Also, the photovoltaic systems should be more durable and dependable operating in the potentially abusive conditions (dust, moisture, etc.) of terrestrial irrigation applications. Also, better adapted motors, pumps and controls to use energy from this power source should be available.

In our judgment, the biomass energy uses in the mid-term are still not overly promising since the competition for biomass materials and the food/fuel conflict will continue. Conservation practices in irrigation will continue to be meritorious with high payoff in energy savings because even with solar energy the cost of energy will not be small.

We cannot speculate about the conditions in the far term -- beyond 40 years in the future. There are too many unknowns to cloud the future visions. Hopefully, some new major commercial energy supplies such as fusion energy may begin to appear to alleviate the problems of depleting fossil energy.

Energy for Irrigation Systems in Perspective

The energy demands for irrigation, or other agricultural needs, in developing countries cannot be viewed in isolation from other energy requirements of the nation. In arid nations, or if there are long dry seasons, irrigation is quite likely an essential input for increasing food production. This very circumstance exists in much of the developing world (40). In other words, the governmental policymakers should first realistically assess the energy which their nation's agriculture (including irrigation) will require to meet the food production goals. For irrigation, several logical steps can be identified and should be followed. These are covered in the sections which follow.

Water Supply Development

As shown in Chapter II, the energy to develop water supplies is not the major energy requirement for irrigation. Surface water supplies are the least energy expensive to develop and should be developed when available surface water resources and topography permits. Also, the energy cost for operating these systems are the least because gravity flow is frequently possible.

It generally takes more than twice as much energy to develop groundwater supplies as surface water. What's worse, the recurring energy cost of pumping is ever present and the energy for pumping is the largest energy requirement in irrigation. Usually, the selection of supply source is not a choice to be made since the nation must develop whatever supplies are available. Moreover, the energy cost of developing either supply is not the major energy cost of irrigated agriculture. Planners should be aware of the energy costs involved, however modest, so the least energy costly sources can be chosen when selections between supply sources are possible.

Water Distribution System

Extensive field studies in Pakistan and other places have shown that the water losses in canals and watercourse systems are much greater than often realized (51). Some losses, such as seepage, may later be recovered from the groundwater but that recovery takes valuable energy. Governments should lead in providing programs to educate the farmers concerning these losses, and insofar as possible, provide assistance and incentives to help reduce losses in the distribution systems between the supply source and the farmers' fields.

On-Farm Irrigation Systems

When soil and topographic conditions permit, the surface irrigation systems are the least energy expensive to construct and operate. However, surface irrigation systems can be wasteful of water if they are poorly designed and constructed and if fields are poorly leveled. Sprinkler systems are costly both in dollars to install and energy to operate (because of the water pressures required). Trickle systems are very expensive, best suited for distant spaced orchard crops, and generally not economically feasible for developing countries although they are very efficient in utilizing water.

Sources of Energy -- Concluding Comments

The developing countries will need more energy if they are to achieve needed increases in food production. A 1977 analysis of the role of energy in food production in developing countries demonstrated that goals of increasing food production will be difficult to meet unless energy is better used in providing the essential inputs of fertilizer, water for irrigation and others (73). As shown in Chapters III and IV, there are no miraculous new energy sources which will suddenly provide ample, inexpensive energy for irrigation. Each potential new source has its own problems, some of which are very serious. For biomass energy sources a serious problem will be the supply of biomass feedstocks. If a nation is food deficient, the chances are not good that land and other agricultural production inputs can be diverted to producing biomass for fuel. Therefore, along with the ever present economic consideration is the food/fuel conflict.

We are not at all optimistic that direct solar devices will make any significant impact on irrigation pumping in developing countries in the near term future. Such possibilities should continue to be explored, but with understanding of the probable cost of such systems. No government should totally bank on direct solar energy providing a cheap solution to irrigation energy needs.

Wind energy offers promise at selected locations in the near term. This will particularly be so when efficient, wind-driven devices are mass produced in the country adding to the local economy.

The source of energy that will continue to provide most of the energy for irrigation is the traditional sources of fossil fuel, hydroelectric and nuclear now used. The costs will increase as supplies diminish, so good conservation and management practices will increase in importance and government leaders should note this fact. The section on Energy Savings Possible on page 27 of Chapter II and the material in APPENDIX II should be reviewed to recap the potential energy savings possible in irrigation.

Specific Recommendations

At the risk of over-emphasizing the importance of irrigation practices, the following are the areas which will provide the greatest savings in energy use in existing irrigation systems. They are provided in the general order of priority in terms of the savings in energy (and water) that can be obtained.

1. Reduce water losses in the watercourse. Earthen watercourses should be maintained and repaired and, if economically feasible and justified, lined with an impermeable material such as concrete or replaced with underground pipe systems. Lack of money for lining canals or installing pipe should not preclude the repair and proper maintenance of earthen watercourses since the payoff in energy (and water) savings has been shown to be sizeable. A related major benefit is a more dependable water supply more adaptable to providing water to crops in the quantities required to meet peak crop requirements.

2. Improve on-farm irrigation practices. Precision land leveling should be provided. If fields are of irregular shape or the length-of-run is excessive for the soil characteristics, the irrigation system should be redesigned for better efficiency. The irrigation application efficiency in most cases should be 70 percent or more in the small fields in developing countries.

3. The efficiency of irrigation pumps should be checked. Low pump efficiencies should be detected and pumps with very poor efficiency repaired. Large energy losses occur when pumping water with pumps poorly matched to the hydraulic characteristics of the well, or when the pumps are in need of repair. The expense of replacing pumps may not be within economic reach of the farmers, but repair of badly worn pumps is a good investment. Be certain that water is not discharged at higher elevation or greater pressure than required as this wastes energy.

4. Make certain that the actual water requirements of the crops are known so that the amount of each irrigation is proper for the crop needs at that time. Irrigation specialists can provide this information based on the crop, its stage of growth, climatic conditions, soil characteristics

and the frequency of irrigation.

5. Use surface water supplies when possible. The energy required to provide surface supplies is generally less than half that required for tubewells and this does not include the pumping energy required to use groundwater.

Research and Development Needs

A complete book could be written on the agricultural and energy research needs in developing countries. Here, we will only symmarize the research needs, with special reference to the energy used in irrigated agriculture.

First, with fossil fuels becoming less available and more expensive, the most efficient practices possible will be needed because of mounting costs of production inputs. Therefore, practical research and demonstrations on production systems, particularly using the new high yielding crop varieties which require better water management will be needed. Much of this is site specific and should be carried out at field locations in the country which are staffed with research scientists and extension specialists, often with an individual having duties in both functions.

Research should concentrate on adaptive research on crops grown in the region. The benefits of good irrigation practices should be demonstrated. Emphasis should be on systems leading to simple production guides for the farmers in the area. These research and extension centers should concentrate on field research and demonstrations and, therefore, do little basic research.

The resources for agriculture in the country should be inventoried, including climatic records, analysis of water resources, soils capability and geology. The efficient use of fertilizers is essential because of the interrelationship between fertilizer and water requirements. The use of water and fertilizer should both be optimized to save energy from each use. Research on local on-farm water management practices should be given high priority and this includes the physical problems, and also the institutional problems. Irrigation systems often waste water because the timing of applications cannot be controlled to meet peak critical water needs. The soil salinity status should be studied and drainage research projects initiated where soil salinity or water logging is a potential problem and reduces productivity.

Government leaders should recognize the importance of demonstrations of good irrigation practices and promote programs to this end. Education of farmers on what can be done to reduce their energy and dollar costs of producing food can have high payoff.

We do not believe that more research to add precision to existing knowledge of water requirements of crops is of the highest priority. Instead, research on the practical irrigation systems which will provide water to the fields when needed, based on the ample knowledge of crop water requirements currently existing. The developed countries will expand their research on methods to save energy in irrigation and some of these may be adapted to developing countries. Still, the economic cost will be the most serious constraint and efforts should be concentrated on this factor.

Although the likelihood of rapid technological breakthrough in solar pumps may not be great, research on simple systems should continue. The benefits from any advances in solar pumping are potentially too great to do otherwise. The same is true of wind-driven pumping systems.

A Final Comment

> "The optimist proclaims that we live in the best of all possible worlds; the pessimist fears this is true" -- James Branch Cabell

The energy supply in the world is critical, particularly in some developing countries. There is also a shortage of other resources. This creates serious problems. However, we believe that there are opportunities to solve problems that initially may appear difficult, or even impossible.

First, the problem of energy shortages and high cost must be recognized. Then an effort must be made, with full awareness of all the facts surrounding the problems, to muster programs so the problems are understood and all the options explained. This information must then be widely distributed in order for the necessary forces to come into action for a satisfactory outcome to be achieved. This desired outcome will not be achieved without strong leadership by the policymakers in the governments of the world.

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APPENDIX I

World Irrigation by Country in Thousands of Hectares

	1961-65	1966	1975	1978
WORLD	140476	162630	181284	200913
AFRICA	5870	6772	7426	7831
ALGERIA	259	270	300F	280F
BENIN	1	4F	5F	6F
BOTSWANA	2	2	1	1*
BURUNDI	4F	5	5	5*
CAMEROON	3F	5F	7F	12F
CAPE VERDE	2	2	2	2*
CHAD		1	1	2F
EGYPT	2546	2801	2855	2836F
ETHIOPIA	40	55F	55F	55F
GAMBIA	12F	15F	25F	27F
GHANA	11	15F	18F	22F
GUINEA	4F	4F	5F	8F
IVORY COAST	5	14	23*	26F
KENYA	14*	23F	38	44F
LIBERIA			2*	2*
LIBYA	123	165	130F	135F
MADAGASCAR	306F	330F	390F	450F
MALAWI	2	3	6F	10F
MALI	42F	55F	80F	95F
MAURITANIA		3F	6F	6
MAURITIUS	10	15	15	15*
MOROCCO	199	310F	385F	475F
MOZAMBIQUE	44F	60F	65F	60F
NAMIBIA	4*	5F	5F	6F
NIGER	6	15F	22*	30
NIGERIA	11	12*	15*	20F
REUNION	6	6	7	7*
RWANDA			1	1*
SENEGAL	77	106	125F	127F
SIERRA LEONE	1	2F	3F	3F
SOMALIA	165*	165*	162*	165F
SOUTH AFRICA	850	990F	1017	1017*
SUDAN	952F	1150F	1407	1550F
SWAZILAND	20	26	26*	28F
TANZANIA	33F	42*	50F	60F
TOGO	2	3	3*	7F
TUNISIA	74	80	108F	140F
UGANDA	2	4	4	4*
UPPER VOLTA			1*	3F
ZAIRE				4F
ZAMBIA	2	2*	3F	5F
ZIMBABWE	27	46*	50F	60F
N C AMERICA	18406.	20366	22169	23548
BELIZE			1	2*
CANADA	365F	400F	440F	480F
COSTA RICA	26	26*	26	26*
CUBA	200	400F	530F	720F
DOMINICAN RP	113	120F	130F	140F
EL SALVADOR	18	20*	33	30
GUADELOUPE	1	2*	2	2
GUATEMALA	30	53	60*	64F
HAITI	38F	50F	70	70*
HONDURAS	60	60*	75F	80F
JAMAICA	23	24*	30F	32F
MARTINIQUE	1	1	1	6
MEXICO	2900F	3400F	4127	5000F
NICARAGUA	18	30F	55F	76F
PANAMA	15	18F	20F	26F
PUERTO RICO	39	39	39	39*
SAINT LUCIA	1	1*	1	1*
ST VINCENT		1	1	1
TRINIDAD ETC	11	15F	18F	20F
USA	14459	15700F	16810F	16700F
SOUTH AMERIC	4682	5463	6040	6643
ARGENTINA	1064F	1215F	1300F	1540F
BOLIVIA	74F	80*	100	125F
BRAZIL	546F	710F	890F	1050F
CHILE	1086	1140F	1230	1320F
COLOMBIA	231	246F	265F	295F
ECUADOR	444F	443	480F	520F
GUYANA	100	115F	120F	122F
PARAGUAY	30F	40F	50	55F
PERU	1046	1070*	1120F	1180F
SURINAME	14	20F	30F	32F
URUGUAY	32	42*	55F	64F
VENEZUELA	218	260*	312*	360F
ASIA	100303	108180	118189	130980
AFGHANISTAN	2200F	2300F	2400	2600
BAHRAIN	1	1	1	1*
BANGLADESH	581	940	1290	1450F
BURMA	681	816	990	981
CHINA	38300F	41000F	43500F	48000F
CYPRUS	95	102*	96	96*
HONG KONG	9	8*	7	6
INDIA	25523	27190	31640	35300F
INDONESIA	4100F	4230F	4700F	5304
IRAN	4600F	5050F	5500F	5450F
IRAQ	1302F	1410F	1530F	1700F
ISRAEL	142	161	170	213
JAPAN	3358	3325F	3295F	3270F
JORDAN	57	60	67F	65F
KAMPUCHEA DM	72	100*	89*	89F
KOREA DPR	500F	500F	700F	1000F
KOREA REP	830	800F	1020F	1122
KUWAIT			1	1
LAO	13	17*	30F	78*
LEBANON	40	68	85F	85F
MALAYSIA	233	217	298	340F
MONGOLIA	3F	5F	18F	30F
NEPAL	77	110F	117	210F
PAKISTAN	11139	13066	13634	14000F
PHILIPPINES	710F	700F	900F	1113
SAUDI ARABIA	270F	320F	370F	395F
SRI LANKA	361	413	427	536
SYRIA	579	476	619	519
THAILAND	1729	1795	2300F	2600
TURKEY	1336	1600F	1950F	2030F
U A EMIRATES	3F	4F	5	5*
VIET NAM	992F	980F	980F	1400F
YEMEN AR	175F	200F	225F	238
YEMEN DEM	23F	35F	40F	65F
EUROPE	8957	10266	12108	13470
ALBANIA	180	240F	300*	370F
AUSTRIA	4*	4*	4*	4*
BELGIUM-LUX	1*	1*	1*	1*
BULGARIA	846	959	1070	1146
CZECHOSLOVAK	67F	90F	90F	
DENMARK	51F	80F	140F	342
FINLAND	4	10F	30F	55F
FRANCE	460F	730F	780F	866
GERMAN DR	93	134F	159F	160F
GERMANY FR	260F	277F	296F	313
GREECE	530	679	856	925F
HUNGARY	196	365	311	181
ITALY	2420F	2520F	2700F	2880F
MALTA	1	1	1	1
NETHERLANDS	140	190F	240F	270F
NORWAY	3F	4F	4F	7
POLAND	285F	260	288	146
PORTUGAL	620F	621	625C	620F
ROMANIA	207	530	1295	2086
SPAIN	2009	2323	2736	2903
SWEDEN	21F	25*	45F	60F
SWITZERLAND	21F	25F	25F	25*
UK	106	96	86	135
YUGOSLAVIA	128	114	148	145
OCEANIA	1198	1443	1606	1686
AUSTRALIA	1115	1354	1470F	1400F
FIJI	1*	1*	1*	1*
NEW ZEALAND	82	88	135	175F
USSR	9618	10200	12746	16400
DEV.PED M E 1/	27642	29674	31767	32983
N AMERICA	15824	16100	16990	17190
W EUROPE	7079	7696	8710	9578
OCEANIA	1197	1442	1605	1655
OTH DEV.PED	4342	4436	4462	4580
DEV.PING M E 2/	70269	77605	88106	96729
AFRICA	1397	1706	2017	2291
LAT AMERICA	8444	9649	11259	13016
NEAR EAST	14521	15762	17287	18183
FAR EAST	45906	50467	57542	63238
OTH DV.PING	1	1	1	1
CENTR PLANND 3/	51568	55855	61431	[illegible]
ASIAN CPE	40087	42585	45287	50567
E EUR+USSR	11480	12770	16144	20402
DEV.PED ALL	39138	42444	47891	53415
DEV.PING ALL	110336	120190	133393	147290

1/ Developed Market Economy

2/ Developing Market Economy

3/ Centrally Planned Economy including USSR and certain Asian and Eastern European Countries

* Indicates Unofficial Figures

F Indicates FAO estimate

Data are from the 1979 FAO Production Yearbook, FAO Statistics Series No. 28, Vol. 33, 309 p.

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APPENDIX II

EQUATION FOR POTENTIAL ENERGY SAVINGS

In Chapter II, a general equation for potential energy savings is given to assess the energy impact of improving the efficiency of various components of the irrigation system. This includes the efficiency of the individual components in delivering water from the point of supply to the point of use (the crop root zone). When pumps are required, the efficiency of the pump in converting mechanical energy to energy of lifted water can also be included.

This general equation may be expanded to include any additional factors that are related to energy use in irrigation. For example, if the net depth of irrigation is reduced through use of improved crops requiring less water, that factor can be included in the equation. Similarly, the effect of reducing the total pumping lift by changing the pressure (lift) requirements of the field irrigation system, such as shifting from high pressure sprinkler systems to low pressure sprinkler or surface systems, may also be considered.

The more general equation representing the savings in energy requirements resulting from energy conservation improvements, expressed as potential energy savings in percent, PES, is

$$PES = 100 \left[1 - \left(\frac{D_a}{D_b}\right)\left(\frac{H_a}{H_b}\right)\left(\frac{E_b}{E_a}\right)_1 \left(\frac{E_b}{E_a}\right)_2 \cdots \left(\frac{E_b}{E_a}\right)_n \right]$$

in which D is the depth of net irrigation required by the crop; H is the total head (pumping lift) required of the irrigation pump; and E represents the efficiency of the various components of the irrigation system. These include the pump efficiency, the efficiency of the watercourse in conveying water, and the efficiency of the irrigation application system on the farm. The subscript b indicates conditions before improvements and the subscript a, the conditions after improvements. The subscript numbers outside the parentheses indicate the various irrigation system components that are changed to improve the energy use efficiency.

An example can again be used to illustrate the procedure. Consider a case where the following improvements are accomplished.

The net irrigation application required for the crop is reduced from 800mm to 700mm giving $\left(\frac{D_a}{D_b}\right) = \frac{700}{800} = 0.875;$

the total head (pumping lift) is reduced from 50 meters to 30 meters giving $\left(\frac{H_a}{H_b}\right) = \frac{30}{50} = 0.60;$

the efficiency of the irrigation pump is increased from 0.55 to 0.67 giving $\left(\frac{E_b}{E_a}\right)_1 = \frac{0.55}{0.67} = 0.821;$

the watercourse conveyance efficiency is increased from 0.50 to 0.70 giving $\left(\frac{E_b}{E_a}\right)_2 = \frac{0.50}{0.70} = 0.714$;

and the efficiency of water application in the fields is increased from 0.65 to 0.80, $\left(\frac{E_b}{E_a}\right)_3 = \frac{0.65}{0.80} = 0.812$.

The combined effect of these improvements results in the following potential energy savings:

$$\begin{aligned} PES &= 100\,[1 - (0.875)(0.60)(0.821)(0.714)(0.812)] \\ &= 100\,[1 - 0.25] \\ &= 75\% \end{aligned}$$

Therefore, 75 percent of the original energy used can be saved by this combination of improvements in the irrigation practices. Stated another way, only one-fourth as much energy would be required to provide irrigation as before.

Although it would seldom be possible to make all these improvements in a single system, the equation can be used to assess the magnitude of the energy savings resulting from each improvement, individually or collectively.