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MEASURES OF APPROPRIATENESS: THE RESOURCE REQUIREMENTS OF ANAEROBIC DIGESTION (BIOGAS) SYSTEMS

Michael T. Santerre
Research Fellow

and

Kirk R. Smith
Research Associate

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Resource Systems Institute
The East-West Center
1777 East-West Road
Honolulu, Hawaii 96848
USA

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ABSTRACT

Anaerobic digesters have a potential for providing fuel, fertilizer, and a sanitary means of waste disposal in rural areas of less developed countries. Despite these potential benefits, digesters have had a disappointingly low success rate in many LDCs. Poor economics may explain these failures in some cases but poor fits between digesters and local conditions--a lack of appropriateness--can also be a useful indicator.

Using a detailed accounting framework, we disaggregate anaerobic digestion systems into five subsystems, analogous to the subsystem components of the nuclear power fuel cycle. Relying on published information from India and China, we compare 38 fixed- and floating-dome digester models and note qualitative and quantitative differences in their uses of construction and operating resources. Environmental and social resources used in the subsystems are also discussed. A tentative "specifications plate," for anaerobic digestion systems is proposed. This provides quantitative measures of the appropriateness of particular systems in different settings.

1. INTRODUCTION

There are two primary intermediate-term challenges facing the world energy system. The first is to accommodate the great shifts in wealth and power accompanying the evolution of the global petroleum market. The second is to find some means for supplying sustainable supplies of high-grade energy for development of the rural areas of poor countries, areas where 60 percent of humanity now relies nearly entirely upon traditional biomass fuels.

A number of technologies for tapping new sources of energy or for upgrading traditional sources have been proposed for helping meet this second challenge. Clearly, economic viability in its most gereral form is the principal criterion by which most such technologies are to be judged. Achieving more efficient allocation of scarce resources is the central objective in applying the economic criterion and is probably the most important potential of most small-scale energy technologies. Unfortunately, however, the techniques provided by economics for applying this criterion are sometimes difficult to use in practice. Difficulties are encountered, for example, in defining efficiency to incorporate social goals such as equity, incorporating externalities such as environmental impacts, and relying on prices or modifications of prices as data inputs. These problems are well recognized and not without partial remedies.

There is a considerable body of thought, however, that holds traditional economic techniques to be particularly incomplete when applied

to rural societies in developing countries. This dissatisfaction has led to a search for measures of the fit of technologies into rural life that explicitly consider such factors as use of local resources, environmental effects, sustainability, and impact on local culture. (See: UNIDO 1978; Ashworth and Neuendorffer 1980). Forsyth et al (1980), for example, have developed and tested an appropriateness index that measures the engineering potential for increases in labor intensity in various technologies. The information provided by such measures can be used not only to construct non-economic appropriateness indices and other predictors of success but also to modify price information to improve more traditional economic analyses.

In this study we demonstrate a framework that allows for consistent comparison of resource requirements among different classes and models of small-scale energy technologies. We follow the procedures outlined in Criteria for Evaluating Small-Scale Rural Energy Technologies: The FLERT Approach (Fuel-Linked Energy Resources and Tasks) (Smith and Santerre 1980). The FLERT approach is an adaption of two techniques having growing application to large-scale systems in developed countries to the analysis of small-scale energy technologies in developing countries. The first of these is materials accounting based on process models (see Carusso et al. 1975; Grenon 1979). We have expanded this accounting scheme to include not only physical resource requirements such as bricks but also to include social resources such as labor and environmental resources such as climatic factors.

The second part of the FLERT approach is to identify the tasks performed by the energy outputs of small-scale energy technologies. This is an extension of the work being done in the developed world that focuses on the services done by energy rather than merely on the energy content--to minimize the costs of producing a tonne-kilometer of freight transport rather than focus on providing the cheapest alternative to diesel fuel, for example (see Carhart 1979; Sant 1980; Reister and Devine 1981). In our extension to rural developing areas, we have included social tasks such as providing employment and environmental tasks such as sanitation in order to more accurately reflect all the ways in which small-scale technologies interact with day-to-day life.

What follows here is an elaboration of the first part of the FLERT approach--resource accounting--for one particular set of technologies--anaerobic digestion. This results in a profusion of information in common with the output of other process models. Boiling this down to a manageable and useful set of indicators for comparing different technologies is necessary in order to make this approach useful for policy making.

Such a set of key indicators might take the form of a "specifications plate" that would allow different technologies to be compared on the basis of their most important parameters in a consistent manner. This is analogous to the specifications used to compare new cars, for example, where horsepower rating, compression ratio, passenger capacity, fuel efficiencies, seat configuration, cargo volume, and so forth cannot be easily converted to a common metric. Buyers must make trade-offs

among these characteristics according to their own needs and operating conditions as well as the relative prices. Consequently there is no such thing as the "best" car (best being a function of the fit with the customer's needs). This implies that there will always be a need for a variety of car models; for even though the basic function of cars is to provide passenger transportation, they serve other functions as well. The most critical factors and consistent measures for them have evolved over many decades and hundreds of millions of cars such that the list of specifications in automobile brochures are comparable and reasonable reflections of consumer needs and desires. Unfortunately, no such set of specifications has yet been developed for small-scale energy systems and meaningful comparisons are very difficult as a result.

Of course many products serve multiple functions and this is especially true with products that are consumed in the end-use sector--"the level at which life is lived" in the words of Heilbroner (1959). In intermediate production, by contrast, one might expect that economic factors would be sufficient to characterize technologies. This interaction with life at the level it is lived is, perhaps, the way in which household and community energy technologies differ most from their large-scale counterparts. Since standard economic measures may be incomplete predictors of success, a specifications plate may be helpful. In addition, unlike automobiles, if such systems are to be constructed as well as used locally, these specifications must include not only performance characteristics, but also measures of construction parameters in order to fully reflect the fit with local conditions and needs.

2. ANAEROBIC DIGESTION TECHNOLOGIES

Anaerobic digesters (sometimes called biogas plants) are often described as a means of providing the energy needs of rural areas in developing countries, while also leading to other improvements in rural living conditions and environment. Briefly, anaerobic digestion is a process in which organic materials are degraded by bacteria in the absence of air into a methane and carbon dioxide mixture (biogas), and a residue (sludge and effluent) consisting of inorganic and organic compounds, and bacterial cells (see Singh 1973, 1974; Sathianathan 1975; Meynell 1976; National Academy of Sciences 1977; ESCAP 1980).

Anaerobic digesters seem to offer many potential advantages for rural areas. They can extract the energy content of animal and human wastes while preserving the fertilizer value of the wastes. In addition, digesters can assist in alleviating two of the most serious rural environmental health problems--contamination of water supplies by human waste and air pollution from the combustion of solid biomass fuels for cooking. There are also potential indirect benefits. Some anaerobic digesters can be constructed utilizing local labor and material resources rather than increasing the reliance on imports into the village from urban or foreign sources.

Despite these apparent benefits, the rate of failure or abandonment of anaerobic digesters, or expression of dissatisfaction by persons who have installed them, is alarmingly high in many developing regions (Coulthard 1978; Siwatibau 1978; Prakasam 1979; Ratasuk et al.

1979; Karki et al. 1980; Dandekar 1980; Bhatia 1981; Sharma 1981). Because truly "appropriate" technologies should be intimately integrated with rural life and enjoy a general acceptance among the majority of rural people, the owner of such a device that has a technical problem should, logically, make every effort to make it operational again (Ratasuk et al. 1979). Since such efforts are often not made, it seems fair to say that digesters have not fit well with rural life in many locations. In other areas, most notably Szechuan Province in China, digesters apparently have become integrated thoroughly into rural economic and social patterns. Trying to understand what makes a successful fit between particular digesters and local conditions has become the focus of considerable effort. The extent of local resources needed for construction and operation is often singled out as an important factor (Dandekar 1980).

Here we will limit our analysis to simple and relatively inexpensive types of "community-scale" and "household-scale" anaerobic digesters, and exclude systems that can be roughly described as "agricultural industry scale" systems, such as the successful operations in the Philippines at Maya Farms (Maramba 1978). We concentrate on household and community digesters because they are likely to interact at a more intimate level with the rural social system than digesters processing wastes from agricultural industry such as large piggeries. Because agricultural industries are likely to have more capital to risk, more willingness to experiment with innovative technologies, and more urgent needs for better waste management, they will be more likely to successfully use these more sophisticated and expensive high-performance digesters which appear inappropriate for most low-income households and communities, at least in the near term.

In order to examine the resource requirements of digesters, the anaerobic digestion system is disaggregated into more manageable subsystems, analogous to disaggregating nuclear power systems into component parts of the nuclear fuel cycle. For anaerobic digesters these include the following subsystems: (1) digester construction; (2) on-site digester operation and maintenance; (3) feedstock management; (4) digester residue management; and (5) biogas distribution.

The information that we present below has been drawn principally from literature on biogas plants in developing countries, particularly from India and China (Ramakrishna 1980). Although the available published data base is insufficient for establishing and cross checking a complete specifications plate, we offer a partial plate for illustration and to invite comment.

3. SUBSYSTEM I. DIGESTER CONSTRUCTION

(a) Manufacturing or obtaining construction materials.

This phase involves obtaining locally available or locally produced construction materials or materials produced elsewhere and imported into the village.

Information from developing countries concerning the resource requirements for manufacturing construction materials is relatively scarce.

Table 1 includes only the quantity of energy and labor used in the manufacturing of these materials, and does not include, for example, the quantities of ore, clay, or limestone also required. The assumptions and system boundaries used in the cited resource audits are generally not stated, and are likely to vary among the different references. Hence, caution should be used in their intrepretation.

Although metals are not likely to be locally produced (the village boundary is the principal geographical system boundary used in FLERT analyses), the quantity of fuels used to manufacture steel is presented because of the national implications of using steel as a construction material. These data are also provided to illustrate the problem of comparing data using different system boundaries.

For example, the National Productivity Council of India (NPC 1970) reports that the national average for energy use in the manufacture of iron is 330 kilograms of coal per 1,000 kilograms of iron (the system boundary appears to include only the blast furnace step). By comparison, the production of 1,000 kilograms of steel in the United States is reported by Reister (1978) to require 1,200 kilograms of coal and/or coke, 420 cubic meters of natural gas, and 140 liters of petroleum fuels. This difference is largely a result of a broader system boundary in the United States example, including mining ore, transportation, and other related activities.

An estimate of the resource costs for the manufacture of the steel gas collector of a 1.2 cubic meter per day floating dome digester was

obtained in an interview with a machine shop owner in Sri Lanka (Santerre 1981). This gas dome (1.3 meter diameter x 1.2 meter high) requires about 160 kilograms of mild steel sheet and angle iron. Nine person days of skilled labor (arc-welding), and six person-days of unskilled labor are needed to manufacture one dome. In addition, five kilowatt-hours of electric power are needed to power the arc-welding machine, and four liters of paint are applied for corrosion protection.

Our only source of information on the labor and environmental requirements for procuring locally-available construction materials was from the Chinese biogas literature, where it was reported that 20 person-days were needed to transport materials for construction of a 4.0-cubic-meters per day (biogas production capacity) digester (van Buren 1979). This is almost 60 percent of the labor required to construct the digester itself. The cited reference did not mention the labor required to extract the materials from the ground, nor the environmental requirements (land, etc.) for doing this.

(b) Constructing the digester.

This phase includes the construction of the following components: (a) the digester pit; (b) the gas collector; (c) the feedstock inlet and residue (sludge and effluent) outlet; and (d) the slurry mixing tank.

Resource requirements of the digester construction subsystem: per unit of biogas production capacity. The principal materials used in the construction of 38 different fixed- and floating-dome digesters are

presented in Table 2. Minor (though important) items such as tools, valves, and paint are not included.

We report the capacities of the digesters in relation to the cubic meters of gas they are rated to produce per day, as is the convention in most of the Indian digester literature (Sathianathan 1975; Subramanian 1977). The actual production of biogas by floating-dome digesters, however, is often considerably less than the rated capacity (Rajabapaiah et al. 1979; Karki 1980). We did not incorporate any correction factors into the data presented in Table 2.

The fixed-dome digesters described in the Chinese literature are rated in terms of the pit size of the digester with a coefficient provided for estimating the biogas production capacity of the system during a particular season or for a particular feedstock or loading rate (van Buren 1979). For comparative purposes, we use the value of 0.20 cubic meters of gas per day per cubic meter of pit, which corresponds to gas production during the summer in China (Chen and Xiao 1979; van Buren 1979). In countries located in warmer climates, such as Sri Lanka, biogas production rates may increase to as much as 0.5 cubic meters of biogas per cubic meter of pit (Santerre 1981).

The principal difference in the use of construction materials between fixed- and floating-dome digesters is the use of iron or steel by the floating-dome type in its gas collector (Table 2). Alternative materials for the collectors (e.g. plastic, rubber, concrete) of floating-dome digesters are being tested (Seshadri 1979), although none of these is in widespread use at this time.

With the exception of steel and iron, however, neither of the two types seems to be inherently more efficient in materials use than the other. Differences do arise among different models within a given design, and therefore individual models must be evaluated in the context of the local availability of construction materials.

Water is used as an ingredient in concrete, but as it was generally not reported, it is not accounted for in Table 2. The quantity of water used in making concrete, however, is relatively insignificant compared to that required in operating a digester (see below).

Although a large land area is not required for a digester, lack of land can limit the location of digesters in areas with densely clustered buildings. A household-scale system might require about 25 square meters (5m x 5m) of space for the digester and suitable workspace, while a community-scale system could require 140 square meters (12m x 12m).

In addition to the land requirements, consideration must also be given to other environmental factors, such as site accessibility, slope, water table, soil drainage characteristics, and proximity to trees. These will affect not only the siting of the digester, but also the selection of construction materials (van Buren 1979) and the labor requirements for its installation. For example, van Buren (1979) reports that poor soil conditions could increase the labor needed by 30 to 40 percent.

Some data on the labor requirements for building a digester are presented in Table 2. The most interesting aspect of this analysis was that there appears to be a certain diseconomy of scale in labor intensity for the some of the Chinese fixed-dome digesters. The reason for this is not given in the original report (van Buren 1979), but could be related to the complexity of the task of building large dome-shaped brick structures.

The quantity of skilled and unskilled labor required to construct a 3.0-cubic-meter digester has been tabulated by the Murugappa Chettiar Research Center (MCRC 1979). They report that approximately 20 person-days are required for manual tasks, such as earthwork, and 9.5 person-days of work by a skilled mason are needed. (Labor required for other construction tasks is reported in monetary units rather than person-days.) Other examples are provided in the footnotes to Table 2.

Other social resources required for constructing a digester include sources of credit, a system for obtaining and distributing construction materials, and community organization in the case of community digesters. Discussion of these factors are fairly common (Khadi and Village Industries Commission [KVIC] 1978; Sathianathan 1975; Bahadur and Agarwal 1980), and it is clear that such resources are important.

<u>Resource requirements of the digester construction subsystem: per unit of biogas produced.</u> Energy systems are not operated at 100 percent of their rated capacities throughout their lifetimes for a number of reasons: (1) energy demand is periodically less than the system is capable of producing; (2) feedstock materials (e.g. agricultural wastes) might be

subject to variations in availability; (3) environmental conditions could affect the efficiency of gas production by the system (e.g. anaerobic digestion is affected by temperature; see Idnani and Varadarajan 1974); and (4) many energy systems require at least occasional shutdowns for repair and maintenance. In addition, because of design and construction factors and differences in the environments in which digesters are operated, their life expectancies will differ. Thus it is useful to examine the use of resources by digesters in terms of a quantity of biogas produced rather than biogas production capacity.

For example, fixed-dome digesters, by virtue of their being almost completely underground, are relatively well insulated against low winter temperatures. Because floating-dome digesters are partially aboveground, and a low-cost and effective means to insulate or heat them has not been devised, the winter period of low gas production may be longer than for a fixed-dome system of an identically rated capacity operating in the same location.

Similarly, digesters receiving plant residues might have to be cleaned more frequently. It might also be necessary to periodically open the digester and remove its contents to correct gas or effluent leaks, or if large quantities of fertilizer are needed at specific times during the year. This can interrupt gas production for one or two months.

As already mentioned, the quantity of energy that a system produces is also related to its life expectancy. Some estimates of the length of service of digesters are as high as 25 to 35 years (Mukherjee 1974; VITA 1979). However, these values seem high, especially for

floating-dome digesters (see Santerre and Smith 1980). The estimated life expectancies of some major components of floating-dome digesters in India are given in Table 3.

A comparison of two digesters with respect to the construction materials each requires, prorated over the expected gas production during the lifetime of each digester, is provided in Table 4. Both digesters are assumed to have correctly rated production capacities (i.e. are capable of producing 2.8 cubic meters of biogas per day). Also, both are assumed to be operated over their lifetimes at 75 percent (average) of their rated capacities. We are assuming (for illustration) that the floating-dome digester has only a 10-year life expectancy (due to gas collector corrosion), and that the fixed-dome digester has a lifetime of 15 years. The construction materials are given per 10,000 cubic meters of biogas in order to compare the two digesters on a similar footing (about 220 gigajoules).

This method can result in more realistic comparisons of different digesters, but only if reliable information is available concerning the digesters' capacity factors and their life expectancies.

4. SUBSYSTEM II. ON-SITE DIGESTER OPERATION AND MAINTENANCE

The major elements of the Subsystem II are: (a) on-site preparation of feedstock and digester loading; (b) process monitoring and control; (c) cleaning; and (d) preventive maintenance, trouble-shooting,

and repair. Other operations, such as collection of feedstock or residue distribution, are discussed under other subsystems.

Daily activities. In a comparison of renewable energy systems for developing countries, French (1979) assumes 0.75 hour per day is required to mix inputs and operate a three cubic-meter plant. These labor requirements (per cubic meter per day capacity) seem to be relatively independent of the scale of the digester; since the community system described by Bhatia and Niamir (1979) employed two persons, which works out to be approximately the same.

This assumption of constant operating cost per unit of biogas production capacity also seems to be borne out by information presented by Ghate (1979) in a survey of digesters installed in India (Figures 1, 2). Although the initial costs of digesters (per unit of production capacity) showed a definite economy of scale, the operational costs (on the same basis) were approximately the same over the size range surveyed.

It is important to note that these estimates are gross rather than net in that some of these activities might have occurred anyway if the digester had not been built. Others would not be conducted if a digester were not present, and there may be displacement of labor from activities that were performed prior to the installation of the digester, such as making dung cakes for fuel. However, determination of net resource needs cannot be made in the absence of situation-specific data. Unless otherwise stated, we will use gross resource estimates because of this limitation.

Process monitoring and control of a digester involves monitoring indicators of the performance of the digestion process, such as pH, rate of gas production, and the color of the flame of the biogas burner, and attempting to remedy problems that arise in the anaerobic process (e.g., by changing the rate of feedstock addition). In village settings the resource requirements for this are probably minimal, because elaborate monitoring techniques requiring special training, chemicals, or equipment are probably impractical and unnecessary.

Seasonal, annual, and nonperiodic operation and maintenance activities. Typical activities in this category include periodic cleaning, repairing gas or water leaks, and painting ferrous components to prevent corrosion.

The resource requirements for these activities depend particularly on the type of the digester and types of feedstock. Interviews of the owners of 173 household digesters in India indicated that most of the digesters were operated for periods up to five years without cleaning (Moulik et al. 1978). By comparison, fixed-dome digesters in China are typically emptied and cleaned annually or semi-annually (van Buren 1979), interrupting production for one to two months (although it can be done in winter when gas production is low).

Estimates for painting the gas collectors of floating-dome digesters are given in Table 5. These relatively small resource requirements of materials and labor belie the importance of painting, for many of the problems of floating-dome digesters have been attributed to the

lack of preventive maintenance (Moulik et al. 1978; Karki et al. 1980; Bhatia 1981; Sharma 1981).

5. SUBSYSTEM III. FEEDSTOCK MANAGEMENT

Included in this subsystem are the resources required to grow, collect, store, and prepare feedstock and transport it to the digester site.

Many types of raw material are potentially usable by anaerobic digesters, and water, of course, is essential. Organic feedstocks include human and animal body wastes, agricultural crop residues, forest and tree litter, household food wastes, and aquatic weeds. Organic materials that are more resistant to anaerobic digestion can be pretreated with enzymes or acids or by other methods. However, such techniques have only a limited potential for rural community and household systems due to their expense and sophistication.

The quantity of water used for operating a digester is about equal to the "fresh" weight of the biomass added (Barnett et al. 1978; National Academy of Sciences 1977), although this will vary with the biomass used and the season (van Buren 1979). In the case of drying the sludge, the net requirements for water are quite high--the water becomes unavailable for other purposes. If wet sludge is used, then although the gross requirements are the same as if it were dried (requiring the same quantity of water as feedstock), the net requirements are much smaller. This is

because the water remaining in wet sludge is shared by a different activity (e.g. irrigating a crop). Nevertheless, the gross requirement for water is quite large and can be a limiting factor in areas where water is scarce. For example, a 2.8-cubic-meter digester will need about 80 kilograms of water daily, or about 20 tonnes per year. The water requirements will depend, of course, on the degree to which the feedstock has been dried.

Biogas yield per unit of feedstock is affected by temperature, hydraulic residence time (a function of loading or dilution rates and digester volume), and the chemical composition of the feedstock (Meynell 1976; National Academy of Sciences 1977). For example, the chemical composition of cattle dung changes rapidly within a relatively short period, as illustrated in Table 6. The impact of these parameters has been assessed in laboratory conditions; however, adequate information on all of these factors is seldom given for actual operating systems in the developing country biogas literature. Some estimates of the quantities of organic raw materials required to provide biogas as cooking fuel for a family of five persons are given in Table 7.

Estimates of the biogas needs of a family of five range from 1.0 to 3.5 cubic meters per day (Singh 1974; Garg 1978; van Buren 1979). If the range of values for biogas yields per kilogram of cattle dung (e.g.) is factored into the calculation, the resulting estimates of the dung requirements for producing biogas for a family of five ranges between 12 and 110 kilograms per day! The number of cattle required to supply this quantity of dung will depend both on the rate of manure production of the

cattle and the recoverability of the dung (which will depend in part on whether the cattle are allowed to roam or are kept in a confined area).

Bahadur and Agarwal (1980), for example, estimate that under average conditions (at their study site), the amount of recoverable manure from cattle is approximately eight kilograms per animal. Thus, the number of cattle required to supply dung for a household digester could range from 2 to 14, based on the figures presented in Table 7 and Bahadur and Agarwal's estimates. It is not known, however, what proportion of the uncertainties in the analyses given here is due to data unreliability, or to actual differences in the biogas needs of families, recoverability of dung, or gas yield.

Resource requirements for producing, collecting, storing, and transporting raw materials. The day-to-day labor costs of operating a digester are presented by French (1979), who bases his analyses on the assumption that the amount of labor needed to collect dung for digestion is the same as was needed to collect the fuel formerly used for cooking.

Although he assumes that the net labor requirements for collecting dung are zero, French does estimate that 0.5 hours per day are needed to haul water for a household-scale digester (Table 8). French employs the concepts of gross and net requirements to avoid double counting. By this method, the resources that would normally be invested for purposes other than anaerobic digestion should not also be counted in the net requirements for digestion. Thus, French should probably should have included the labor for hauling water as a gross rather than what appears to be reported as a net requirement. That is, while the farmer is described as distributing

digested sludge in a wet state (the sludge serving both as a fertilizer and as irrigation water for the crops), he may also have hauled water previously for irrigation alone. This methodology must be used carefully in distinguishing a household's new activities (undertaken after a digester is acquired) from its previous activities.

Some preliminary data collected by informal interviews of several householders with biogas plants in Sri Lanka, indicate that the gross time requirements for feedstock management are highly variable. Household digesters connected directly to latrines required almost no additional labor (except when kitchen wastes were added), while on the other extreme, households that had to walk some distances to collect cattle dung from fields, roads, or pathways spent up to an hour per day collecting dung and water feedstock (Santerre 1981).

To provide another example, since it is probable that cropland or grazing land would be used whether or not crop or livestock wastes are exploited for anaerobic digestion, there is no reason to count this land as a net requirement despite the fact that it is essential. However, if new facilities are necessary (e.g., for storing wastes or confining cattle), these resources should be included.

6. SUBSYSTEM IV. DIGESTER RESIDUE MANAGEMENT

The management of residues (sludge, effluent) following removal from the digester involves a number of possible activities: (a) drying or

chemical treatment; (b) storing; (c) transporting; and (d) utilization or disposal.

The residue can be dried in order to reduce the concentration of toxic substances (Sathianathan 1975; Maramba 1978), or to reduce its volume to facilitate handling and storage. Since a percentage of the harmful pathogens or parasites present in wastes will survive anaerobic digestion, further treatment may be desirable. McGarry and Stainforth (1978) report that in China twelve kilograms of 20 percent ammonia solution are added to one cubic meter of sludge two days prior to using the residue in order to disinfect it. Schistosome eggs are killed by adding lime at the concentration of one kilogram per ten kilograms of sludge.

The amount of land required to dry the residue will be determined by the rate of sludge production and local environmental conditions, including temperature, humidity, wind speed, precipitation, and soil porosity. Sathianathan (1975) suggests that a roof might be required over the drying area to avoid rewetting of the sludge by rainfall.

Because fertilizers are usually applied at specific times during the year (Sathianathan 1975), a storage facility might be required. If a household-scale system receives a daily input of 150 kilograms of feedstock, then the digester residues removed daily will be about 140 kilograms. If the sludge is applied as fertilizer to agricultural lands on a semi-annual basis, approximately 25 tonnes of watery materials (assuming no evaporation or seepage) must be stored. For a two-meter-deep pit, 12

square meters of surface area would be required. The residues could also be composted prior to use.

Digester residues can be transported by foot (or hoof), vehicle, or pipeline (or sluice) to the site where they will be used. In China some digester residues are transported by canal boat. French (1979) estimates that the labor requirement for distributing 140 kilograms of sludge from a household digester is about 0.75 hours per day (Table 8), which apparently assumes that the sludge is used in a watery state. Interviews of several households using biogas plants in Sri Lanka indicate that the gross time requirements for residue management range from 0.1 to 1.0 hours per day (averaged over several seasons), and depending on the quantity of residue produced and whether it was applied to nearby home gardens or fields further away from the digester (Santerre 1981). As already mentioned, this labor should be classified as a gross requirement if the farmer formerly hauled water to irrigate the crops and hauled fresh dung to the fields as fertilizer.

Digester residues can be used either in a dried state or in a watery state. The possible final dispositions are summarized as follows: (a) land or water disposal (dumping), with no intention to fertilize or otherwise benefit the receiving area; (b) application to land for fertilization, soil conditioning, or plant-watering; (c) application to aquacultural ponds or other bodies of water for fertilization or other purposes; (d) feeding directly to livestock; (e) combustion of dried residues as fuel; and (f) conversion of dried residues into other fuels by technologies such as pyrolysis.

Very little information seems to be available concerning the resources required to apply or dispose of digester sludge, but Table 9 illustrates some of the possible tradeoffs in using watery or dried residues as a source of nitrogen, in comparison to other forms of fertilizers. This comparison is simplistic in that, for example, Table 9 does not account for the non-nitrogen benefits of sludge such as its phosphorus content, or the value of water in watery sludge. It does give an idea of the relative labor costs for applying nitrogen in various forms.

A farmer need only apply two kilograms of urea fertilizer to realize the benefits of one kilogram of nitrogen. By contrast, and assuming that the nitrogen in both forms of fertilizer is equally accessible by the plants in the field, 80 kilograms of dried sludge or 680 kilograms of wet sludge must be applied to achieve the same benefits! Further research on the resource implications of this aspect of digesters is important inasmuch as fertilizer and soil conditioning benefits are claimed as an important advantage of using anaerobic digestion systems in rural areas.

7. SUBSYSTEM V. BIOGAS DISTRIBUTION

Biogas, while fairly versatile when used with stationary equipment, is not readily compressed or liquefied, and therefore is of limited use for powering vehicles or machines located any distance from the digester. Consequently, biogas does not compare favorably in terms of energy density with some of the fuels it replaces, such as kerosene, diesel fuel, fuelwood, and charcoal (see Smith and Santerre 1980).

Biogas can be distributed to end-use devices by either pipe or refillable container, or can be used to generate electricity that is distributed by a power transmission system. We include the following as subsets of the biogas distribution subsystem: (a) pipelines and refillable containers; (b) valves for regulating pressure and flow rates; (c) gas conditioning devices to remove impurities (carbon dioxide, water, hydrogen sulphide); and (d) storage devices to supplement the storage capacity of the digester's gas holder.

As is true for the Feedstock Management and the Digester Residue Management subsystems, the resource requirements of the present subsystem will strongly depend on the distance between the origin of the materials and the place of use. A survey of the owners of household digesters in India indicated that most of the systems were less than 25 meters from the residence, requiring only a small quantity of pipe or hose (Moulik et al 1978).

The significance of the distance relationship is evident in statements by Ghate (1979) and Bhatia and Niamir (1979) that the economic gains in constructing larger scale community digesters (instead of household digesters; see Table 2; Figures 1 and 2) might be offset by the economic costs inherent in the greater distances involved in dung collection or gas and sludge distribution. This is dependent, however, on the housing density in the community; an economy of scale could occur in relatively tightly clustered communities. Although we do not have data on the resources used for distributing biogas from community digesters, we do

have preliminary estimates of the materials requirements for distributing electric power generated from biogas produced by an 84 cubic meter per day digester in Pattiyapola village, Sri Lanka. Approximately 10 kilometers of aluminum cable (7 strands x 3.4 mm diameter strands) and 140 poles were required to distribute electricity to 40 households in this village (Santerre 1981).

An alternative means of gas distribution for community digesters would involve the use of flexible plastic or rubber bladders, which may require fewer resources than the piping alternative. Patrons would bring the unfilled bags to the digester, fill them with gas, and transport them home and connect them to their household gas lines. The bladders could then be pressurized by putting weights on the bag. This system has obvious advantages over the piping alternative by inspiring householders to conserve their gas supply because they can more easily observe their rate of consumption and the quantity remaining. The bladders would have to be fairly large, however, to be of much use (see Table 7).

Gas conditioning devices (Sathianathan 1975; KVIC 1978) vary in complexity from simple water traps to fairly sophisticated methods for removing hydrogen sulphide (by passing the gas through iron filings) or removing carbon dioxide (e.g. by scrubbing with caustic potash). The tradeoffs involved in the choice between simple and sophisticated procedures in terms of resource requirements, improvements in performance, or changes in reliability of the digester system are not discussed here because of a lack of suitable information from developing country biogas literature.

8. SPECIFICATIONS PLATE

A sample specifications plate will be given in this section to illustrate how the large quantity of information presented earlier might be condensed into the more essential resource indicators describing anaerobic digestion systems. This specifications plate is intended to provide a compact and consistent set of data by which: (a) the anaerobic digestion system can be assessed for its fit with conditions in rural areas; (b) different digesters can be compared with one another; (c) digesters can be compared to other small-scale energy devices; and (d) other types of estimates can be performed, such as assessment of the resource implications of large-scale programs to introduce digesters into rural areas. A complete specifications plate might also include more detailed performance and operating characteristics.

A specifications plate is provided in Table 10 for the physical, social, and environmental resource requirements of a household-scale fixed-dome digester. Information about the resource requirements (especially social resources) of anaerobic digesters is sparse in the published literature. Consequently, some of the data presented in Table 10 are based on our own educated guesses or calculations. These data are given with an asterisk to indicate that they are not based on direct measurements. Other important data might not be given in this example table. Our principal objective in providing this sample specifications plate is to illustrate the concept. Constructing a complete specifications

plate, however, will require better information about this technology than is presently available in published form.

An important additional distinction is provided by the specifications plate in Table 10--geographical distribution. Not only may it be important to know how much labor, for example, is used to fabricate and construct a digester but it may be important to know where that labor will be hired--in the village, nearby towns, or in the city. In the same way it may be valuable to know whether physical resources will have to be imported from outside the region or outside the country. Table 10 only distinguishes the village from the outside (in the table called "national,") but there could be further differentiation.

To establish this distribution exactly would require fairly detailed and precise information about the input-output structure of the nation and village. However, the somewhat imprecise numbers that can be derived from the process models by making consistent assumption about system boundaries may be sufficient for most purposes (Smith and Santerre 1980).

Several assumptions underlie the figures in Table 10. First, we assume that the digester is fed with fresh cattle dung, and that 28 kilograms of dung combined with 28 kilograms of water yield one cubic meter of biogas (Rajabapaiah et al. 1979). Second, we assume that the digester is operated at a 75-percent capacity factor, and third, that it has a 15-year lifetime. Finally, for this example we have assumed that there is no local cement or brick manufacturing.

Based on the original source of data for Table 10 (Singh and Singh 1978), our best judgment is that the following items are not included in the values given in this table: (a) physical resources used for the energy distribution system; (b) physical resources required for the feedstock management subsystem, such as new structures or devices for confining livestock, storing organic wastes, or hauling raw materials; (c) physical resources required for the digester residue management subsystem, such as new structures or devices for removing, storing, treating, transporting, or applying residue; and (d) infrastructural and other social resource requirements. Minor construction materials are not included, such as tools, valves, inlet pipes, pressure gauges, monitoring devices, and similar items. In addition, the land requirements for grazing the cattle are not given.

The calculations used to estimate the labor needed to construct a fixed-dome digester are presented in the footnotes to Table 10. The skill requirements for digester construction are assumed to be 75-percent unskilled and available locally, 20-percent skilled and available locally, and 5-percent skilled and available from outside the village. The requirements for operation are assumed to be mostly unskilled, locally available labor. We do not account for labor needed for training, extension, or other institutional activities.

The locational availability of resources is often cited as one of the most important aspects of "appropriateness."

> Priority should be given to those energy technologies which exploit locally available energy, human, and material resources in rural areas as far as possible, so that the rural income remains in rural areas. (UNIDO 1978)

There are, however, some constraints to using locally available resources: (a) the use of such a resource, although technically feasible, may seriously compromise the efficiency, reliability, or safety of the energy production system; (b) the use of such a resource might be detrimental to the environment, socially incompatible, or create undue hardship on non-users of the technology; and (c) the local resource may have more valuable uses in the rural area than its utilization in anaerobic digestion systems.

Some efforts to implement biogas systems in South and Southeast Asia seem to be partly constrained by digester designs that rely heavily on materials that are scarce in those countries. This appears to be the case for the widespread introduction of floating-dome digesters in India (KVIC 1976) and Nepal (Karki 1980), where steel and cement are often in short supply. As demonstrated in Table 2, neither the floating- or fixed-dome types of digesters appear to have a clear advantage over the other in the use of cement (including lime and plaster).

Although there are local substitutes for cement in rural areas, such as rice-husk cement, we are not aware of any cases (other than laboratory or pilot projects) where the steel or iron used in the gas dome of a floating-dome digester was replaced successfully with locally available materials such as concrete.

The resource measures discussed so far have been intensive in that they indicate resources that are consumed in building or operating digesters. There are also important resources that are not consumed but nevertheless affect the success of digester operations. Temperature is an example of such an extensive resource. Biogas production is quite slow at ambient temperatures less than 20° C and essentially stops at 10° C unless, of course, artificial heating is applied.

The other extensive social and environmental resource indicators presented in Table 10 are subjective and very tentative. An adequate means of comparing these indicators among small-scale energy technologies remains to be developed, and our presentation is intended primarily to create an awareness of the need for such data and analytical techniques. Village organization, for example, is less critical for a household-scale digester than it would be for a community-scale system (see Smith and Santerre 1980). In some cases, villages may be less appropriate recipients of community-level projects than smaller social groupings, such as a cluster of households having common family ties, ethnic backgrounds, and some prior successes with community projects.

The level of sophistication of local jobs required to construct a brick fixed-dome household digester of the types used by the Chinese (Singh and Singh 1978) is higher than for a floating-dome system of similar size. Very precise brick-laying techniques are required for the construction of a brick fixed-dome digester, and faulty construction will likely result in a troublesome digester (van Buren 1979).

Cultural taboos or traditions are perhaps more important factors to consider for this technology than for most other small-scale energy systems if human or pig excreta or their byproducts are being considered as feedstock. There are also important social factors to consider if alterations of traditional defecation and waste management practices in rural areas become necessary (Briscoe 1977).

9. DISCUSSION

Individual anaerobic digesters currently in use in developing countries vary considerably in the quantities of construction materials required. The heavy reliance of certain digester models on steel or cement is reported to be hampering programs to promote digesters in some rural areas. If digesters are to have a significant impact on energy supplies in rural areas, low-cost resource-conserving designs must be tested and promoted.

There may be cases in which successful introduction of anaerobic digesters must be preceded by introduction of the materials supply systems necessary to support construction and operation. Thus, although it is obvious that a local supply of feedstock, such as animal dung, is necessary for a successful digester, it may be true that local supplies of brick and cement are also necessary. The Chinese success with digesters, for example, may be partially attributed to their previous success in local production of basic construction materials (Hawkins and Li 1981). Thus, the choice of optimal sites for digesters might include surveys for local deposits of lime, for example, as well as biomass resources and water.

There is interest in economizing by increasing the scale of digesters. Claims have been made that community plants have "clear-cut" economies of scale in comparison to household-scale digesters (Reddy and Subramanian 1979), but there is little evidence that this is a universal phenomenon. As noted by Ghate (1979), the costs of the biogas distribution system, together with the resources (labor) required to transport dung and sludge, could offset the economy of scale inherent in the actual digester plant itself. Clearly, resource utilization will depend, at least in part, on specific local conditions.

Community digesters have also attracted interest because they can provide services to a broad spectrum of rural households, including those that do not have access to adequat feedstock materials to operate their own household digester (Bhatia 1980). Large variations exist in the ownership of cattle among both households and villages in the Indian subcontinent (Figure 3). If it is assumed that a minimum of four cattle are required to provide adequate feedstock for a household digester, then 60 percent of the households in Fateh Singh-ka-Purva village in India have sufficient cattle to make a household digester a viable proposition, while only about 10 percent of the households surveyed in the Gangetic Plain in Bangladesh enjoy this option (data from Ghate 1979; and Islam 1978). [Note: Fateh Singh-ka-Purva village is one of the few villages, however, where a community digester has been installed.]

Although we have been unable to find detailed documentation, it has been reported that introduction of household biogas digesters can lead

to problems in rural areas of India where dung cakes from cattle droppings are an important cooking fuel (e.g. see Barnett et al. 1978; Bhatia 1980). Reportedly, once a well-off household acquires a digester, it initiates tighter controls over the dung in order to produce more biogas. As a result, some households in the community have their access to cattle droppings for making dungcake restricted. Community digesters may be a means to avoid this problem.

It is too early to determine how widely appropriate community systems might be. However, it does seem likely that they will be most successful in localities where a high level of community organization, cooperation, and spirit are present.

There are alternatives to dung that might be considered for digester feedstock, such as agricultural residues and human excreta. Although human and pig excreta are commonly used in China (van Buren 1979), there have been social and cultural problems in other areas of Asia with the use of these wastes. In Thailand, although pig excreta is a principal feedstock in northern and northeastern regions of the country, the use of such wastes is not common in the south where the population is predominantly Muslim (Ratasuk et al. 1979).

Briscoe (1977) discusses the potential for using human excreta for anaerobic digesters in India, and estimates that the wastes from one person could produce 15 to 20 percent of that person's biogas needs for cooking. However, attempts to introduce the use of such materials in India have had mixed results (Sathianathan 1975; Barnett et al. 1978).

Two important aspects of the fit of anaerobic digesters into the environment are the temporal and spatial relationships of the associated resources and tasks (Smith and Santerre 1980). In addition to accounting for the quantity of dung or other feedstock resources, the frequency of need of the resource and the predictability of its supply will influence the quality of energy service provided by the digester. Fortunately, most types of organic feedstock are either available throughout the year or are readily storable.

The temporal distribution of the labor required for digester construction may well coincide with periods of slack agricultural activity or periods when the soil is more workable and requires less labor to excavate (van Buren 1979). There are also important temporal considerations for the operation of a digester, as the time required to collect and haul organic wastes and water, and to haul and apply sludge, could conflict with other activities (Bhatia and Niamir 1979). Indeed it may be useful to add measures of temporal distribution to the specifications plate.

Use of the FLERT approach provides a detailed and reproducible framework for analyzing the resources exploited and the products provided by this relatively complex technological system. Limited as it is by the available data base, the present application of this methodology nevertheless suggests important areas for more detailed studies in the future. There are, for example, many tradeoffs that must be considered with respect to resource utilization. Such studies would also help to improve economic analyses of small-scale energy production systems

through such techniques as shadow pricing. Considerably more attention could be given to social, resource, and environmental studies to understand how these energy systems can play a large role in improving material well-being in the rural developing world.

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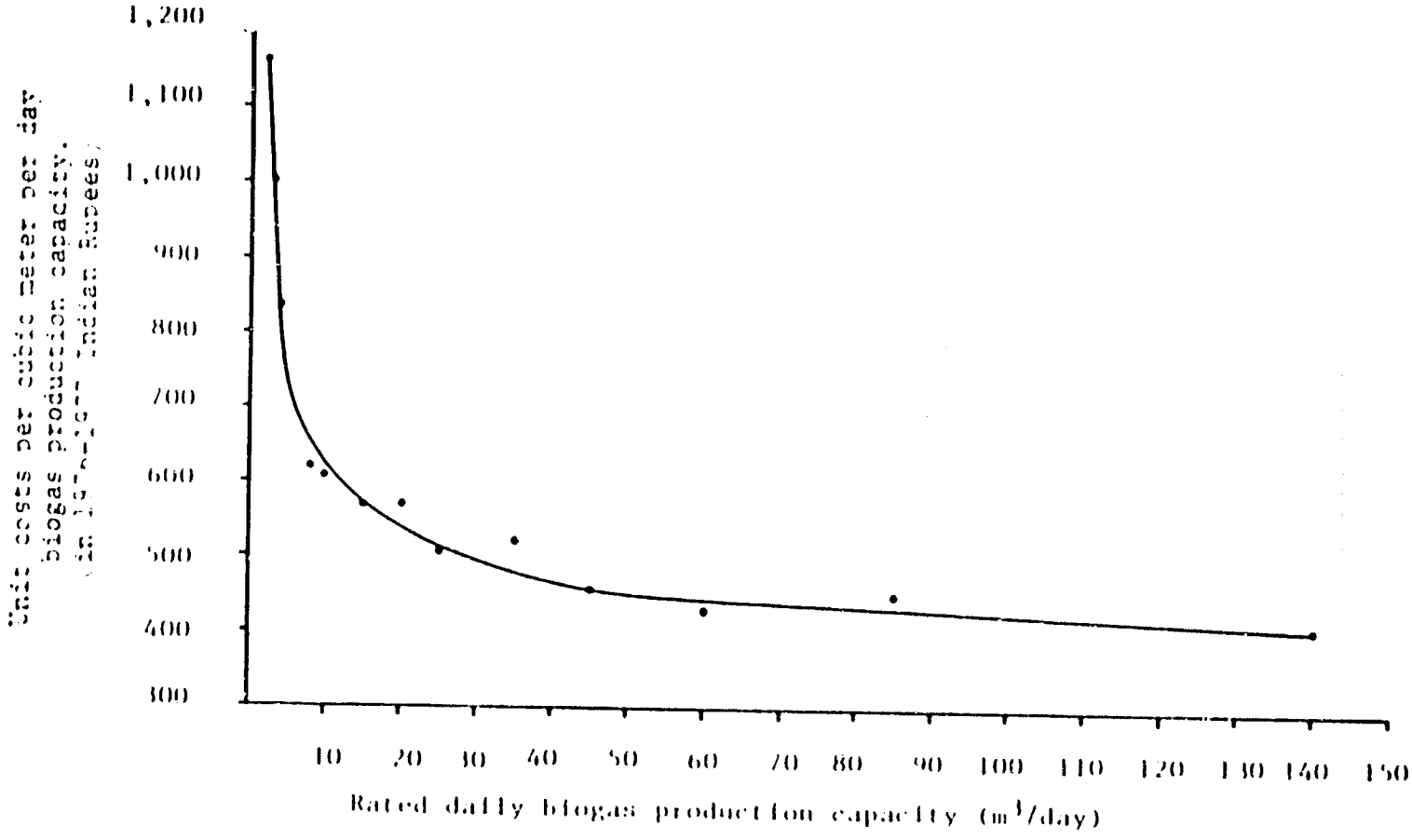

Figure 1. Economies of scale in anaerobic digesters. Comparative initial costs of floating dome anaerobic digesters, per cubic meter of installed daily biogas production capacity. (Adapted from Ghate 1979.)

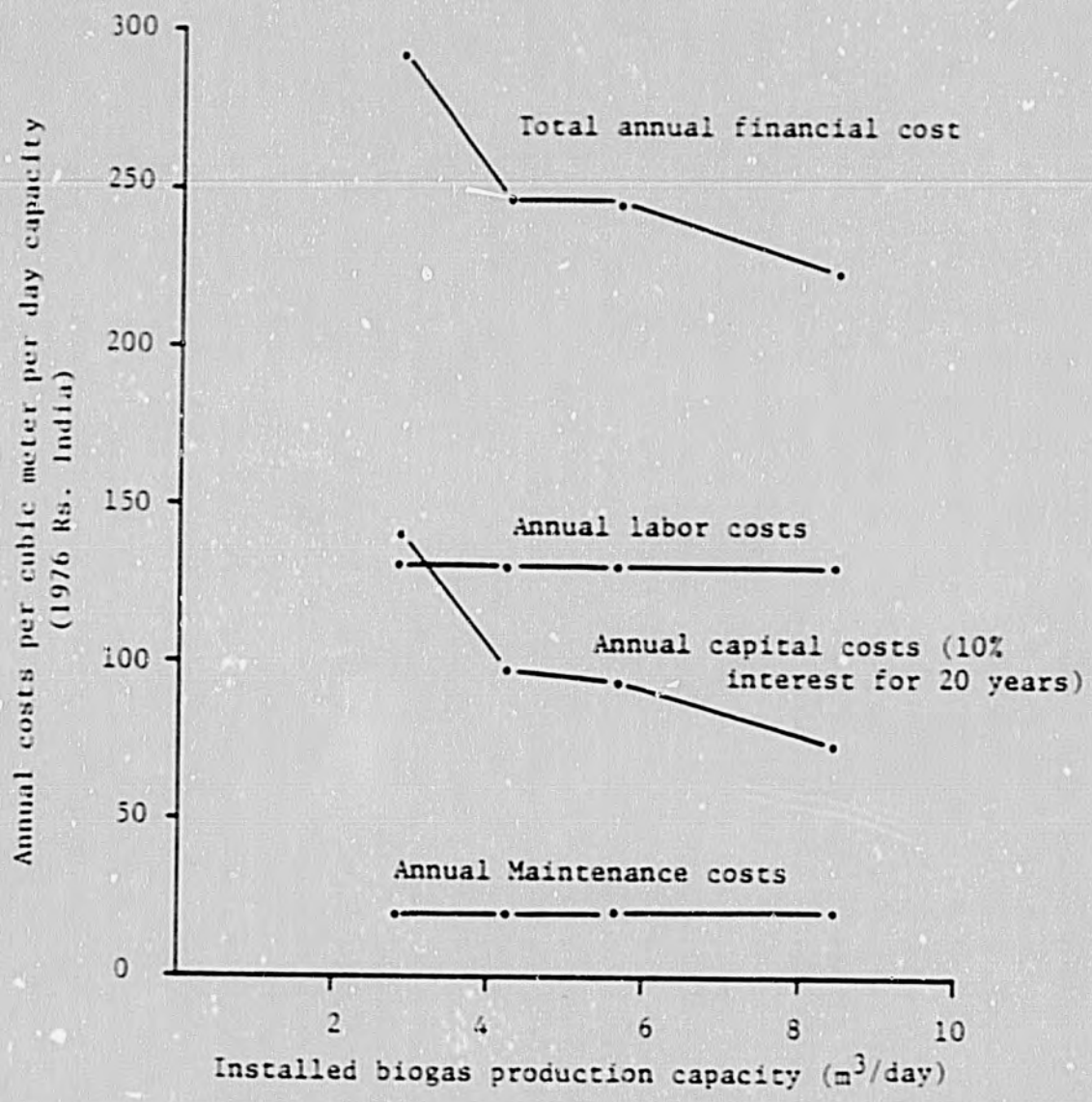

Figure 2. Economies of scale in anaerobic digesters including operation costs. Comparative annual costs of various sizes of various size floating dome digesters, per cubic meter of daily biogas production capacity. (Adapted from Ghate 1979.)

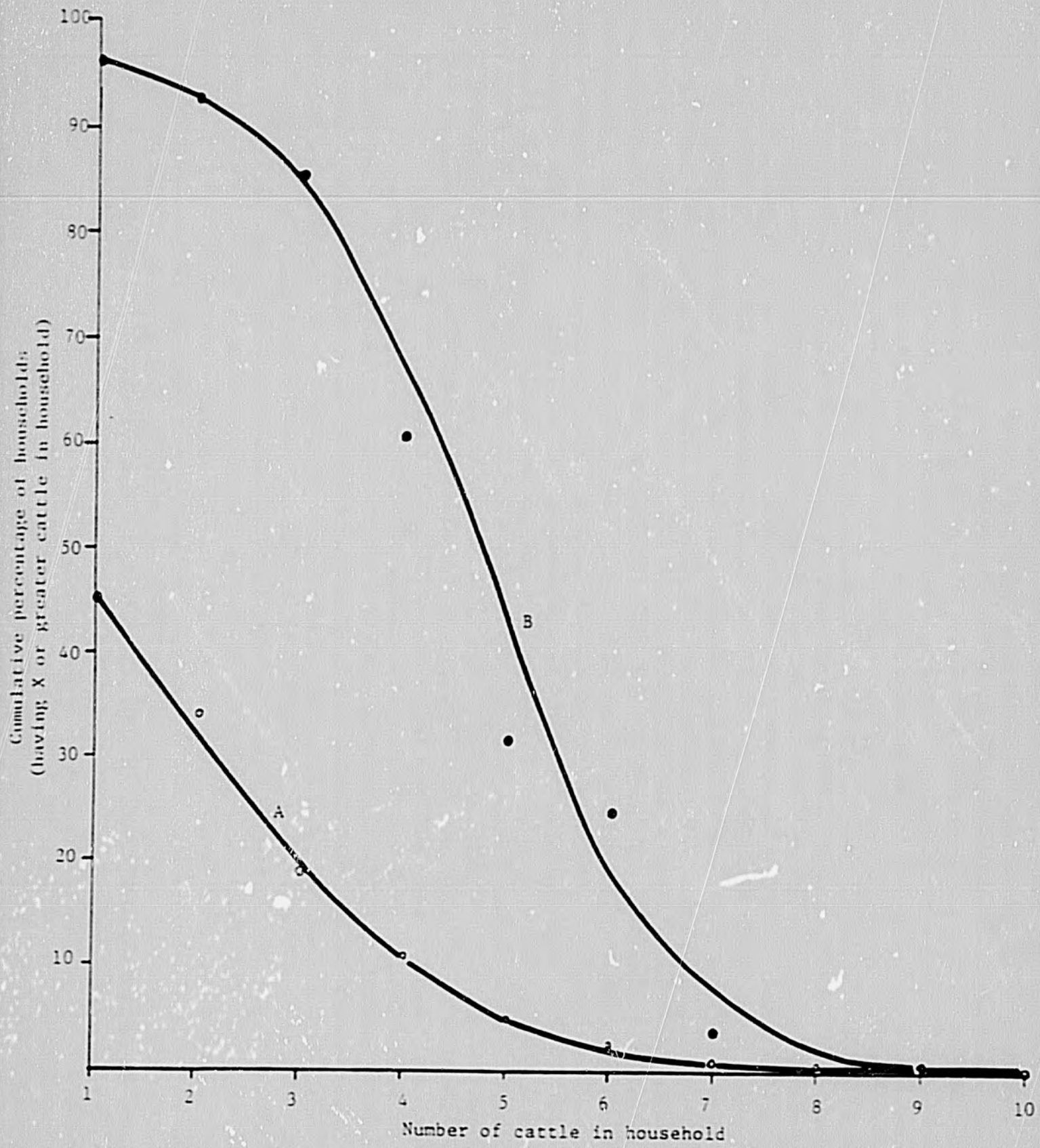

Figure 3. Distribution of cattle ownership. A. among 1,600 households in the Ganges flood plain in Bangladesh (Islam 1978): and B. among 28 households in Fateh Singh Ka Purwa village in India (Ghate 1979). Curves are for comparison only.

Table 1. Resources embodied in construction materials used in anaerobic digesters. [The values presented below may not be entirely consistent since the system boundaries in the original analyses were often not stated, and thus caution should be used in their interpretation; n.a. = not available.]

Construction material	Quantity	Location	Coal/coke (kg)	Fuelwood (kg)	Natural gas (m^3)	Petroleum fuels (liters)	Labor (person-days)	Reference
Bricks	1,000	Bangladesh, Dacca district[a]	220	149	n.a.	n.a.	n.a.	Montreal Engineering Co., (MEC) Ltd., et al. 1976
		Bangladesh, Savar district[a]	119	196-246	n.a.	23.1	n.a.	MEC, et al. 1976
		Bangladesh (national average)[a]	226	141	n.a.	13.4	n.a.	MEC, et al. 1976
		Developing countries (unspecified)[b]	230	n.a.	n.a.	n.a.	1.9	Keddie and Cleghorn 1978
		Developing countries (unspecified)[c]	180	n.a.	n.a.	n.a.	4.8	Keddie and Cleghorn 1978
		Developing countries (unspecified)[d]	210	n.a.	n.a.	n.a.	5.1	Keddie and Cleghorn 1978
		India, Delhi[e]	136-200	n.a.	n.a.	n.a.	4-5	Spence 1979
		India (national average)[f]	200	n.a.	n.a.	n.a.	n.a.	National Productivity Council (NPC), India 1970
		Indonesia, Luwu	n.a.	700	n.a.	n.a.	n.a.	Weatherly 1980
		Sri Lanka, Debahara village	0	290	n.a.	1.2[h]	5.0[i]	Santerre 1981
Cement	1,000 kg	Bangladesh, Chhatak[j]	n.a.	n.a.	212	n.a.	n.a.	MEC, et al. 1976
		India (national average)[f]	300	n.a.	n.a.	n.a.	n.a.	NPC, India 1970

Table 1. Resources embodied in construction materials used in anaerobic digesters. [The values presented below may not be entirely consistent since the system boundaries in the original analyses were often not stated, and thus caution should be used in their interpretation; n.a. = not available]

Iron	1,000 kg	India (national average)[f]	550	n.a.	n.a.	n.a.	n.a.	NPC, India 1970
Lime	1,000 kg	Honduras[k]	n.a.	1,110	n.a.	n.a.	n.a.	Blum 1979
		India (national average)[f]	200	n.a.	n.a.	n.a.	n.a.	NPC, India 1970
		Sri Lanka, Elikawela village	0	720[l]	0	8.2[m]	2	Santerre 1981
Steel	1,000 kg	USA[n]	1,220	0	420	140	n.a.	Reister 1978
		USA[o]	980	0	2	20	n.a.	Long et al. 1978

Footnotes

a. Data are for Country kilns ("stadium-like"). The fuel is furnace oil. System boundaries and other resource inputs are not stated.

b. Data are for a Tunnel kiln, using capital-intensive operations (mechanical excavators, trucks, mechanized brick extrusion and cutting, and artificial drying). Ninety-nine workers are employed, with an annual output of 16 million bricks. We assume a 50-week workyear, and a 6-day workweek. Labor estimates include the winning and transport of clay, but not (apparently) obtaining fuel or transporting bricks. Liquid fuels required for machinery may be included in the coal/coke estimate, as data are reported as tons of coal equivalent.

c. Data are for a Hoffman Ring kiln, using labor-intensive operations (manual preparation and brick molding, bullock cart transportation or hand barrows). About 255 workers are employed, with an annual output of 16 million bricks (same assumptions as in footnote b above).

d. Data are for a Bull's Trench kiln, using labor-intensive operations (see footnote c above). About 375 workers are employed, with an annual output of 16 million bricks (same assumptions as in footnote b above).

e. Data are for a Bull's Trench kiln, with bricks molded by hand. System boundaries apparently include only brick molding and kiln operations. Labor estimate is based upon a reported 120-150 persons employed at the kiln, and a production capacity of 30,000 green bricks per day.

f. No other relevant information on energy use or the system boundary were given.

g. Includes: coconut tree logs: 180 kilograms; rubber tree logs: 110 kilograms.

h. Estimates are for transport of firewood only, a distance of three kilometers (one-way only) at a fuel consumption rate for lorry transport of 10 tonne-kilometers per liter of fuel (Santerre 1981).

i. Includes: winning & transport of clay: 0.83 person-days (pd); kneading clay and water: 0.83 pd; molding bricks, stacking, drying: 1.7 pd; transporting dried bricks to kiln: 0.83 pd; stacking bricks: 0.40 pd; burning bricks (mostly tending fire): 0.40 pd.

j. Gas for grinding clinkers and for firing kilns only. System boundaries and other energy inputs were not given.

k. Forty pieces of wood (size range of pieces: 9-41 kilograms) are needed to produce 0.9 tons of lime. No other energy inputs were given.

l. Coconut logs.

m. Estimates are for transport of firewood and limestone only; firewood transported six kilometers (one-way only) at a fuel consumption rate for tractor-trailer transport of 2 tonne-kilometers per liter; limestone is transported 40 kilometers (one-way only) by lorry at 10 tonne-kilometers per liter of fuel (Santerre 1981).

n. Data are for energy embodied in average steel output, and include extracting and reducing ores and fabricating steel into basic shapes. Original data on fuels are reported in BTUs; our fuel quantity estimates are derived from standard tables.

o. Data are for the blast furnace only.

Table 2. Comparison of the use of construction materials and labor (per unit of rated capacity) by 38 anaerobic digester models. Quantities are rounded to two significant digits.

Anaerobic Digester: Type	Anaerobic Digester: Model or description		Rated capacity (cubic meters of biogas per day)[a]	Quantity per cubic meter of biogas production capacity: Bricks (number)	Cement, lime, plaster[b] (kilograms)	Iron, steel[c] (kilograms)	Sand, cinders gravel, stone[d] (kilograms)	Labor (person-days)
Fixed-dome	Ceylon Electricity Board[A]		1.2	1,200	440	0	1,300	30[e]
	Circular pit of brick, cylindrical[B]	a.	2.0	700	300	0	1,900	12
		b.	3.0	630	270	0	1,900	28
		c.	4.0	600	300	0	1,900	35
		d.	5.0	760	320	0	2,200	50
	Circular pit of brick, large volume/ small mouth[B]	a.	2.0	400	150	0	930	18
		b.	3.0	330	130	0	940	22
		c.	4.0	320	150	0	930	20
		d.	5.0	400	160	0	1,100	36
	Circular pit of round stone slabs and irregularly-shaped stones[B]		2.0	0	82	0	2,700	n.a.
	Circular pit of soft triple concrete[B]		3.0	0	100	0	200	10
	Circular pit with one-piece dry triple concrete cover[B]		4.0	0	120	0	1,100	14[f]
	Janata[C]	a.	2.2	680	140	0	1,700	10
		b.	2.8	1,800	450	0	8,200	38
		c.	2.8	1,200	250	0	3,800	16
		d.	2.8	890	180	0	3,000	15
		e.	4.2	1,100	270	0	4,000	14
		f.	5.6	890	230	0	3,800	15
		g.	5.6	890	200	0	2,600	15
		h.	5.6	890	180	0	2,500	8
	Pit built in shale ground		2.0	0	54	0	12	12
	Rectangular pit of long pieces of hewn stone[B]		2.0	0	120	0	11,000	n.a.
	Rectangular pit of round stones[B]		2.0	0	600	0	7,800	n.a.
	Rectangular pit of triple concrete[B]		2.0	0	790	0	6,000	n.a.
	Sri Lanka Industrial Development Board[D]	a.	2.0	1,000	410	1.7	1,100	25[g]
		b.	7.0	740	270	0	740	14[h]
	Vase-shaped pit of lime cinders and bittern[B]		2.0	50	160	0	300	n.a.
	"Water pressure"[E]		1.2	660	360	0	3,100	24[i]

Table 2. Comparison of the use of construction materials and labor (per unit of rated capacity) by 38 anaerobic digester models. Quantities are rounded to two significant digits.

Anaerobic Digester				Quantity per cubic meter of biogas production capacity				
Type	Model or description		Rated capacity (cubic meters of biogas per day)[a]	Bricks (number)	Cement, lime, plaster[b] (kilograms)	Iron, steel[c] (kilograms)	Sand, cinders, gravel, stone[d] (kilograms)	Labor (person-days)
	"Water pressure," using "3-in-1" soil[D]		1.2	140	480	0	1,800	24[j]
Floating-dome	"BGS"[F]		2.2	0	220	68[k]	1,400	14[l]
	KVIC [G]	a.	2.8	1,000	270	55[m]	1,900	n.a.
		b.	85	560	140	32[n]	800	n.a.
	VITA [H]	a.	2.0	1,400	550	28[o]	6,800	n.a.[P]
		b.	3.0	1,100	420	36[o]	6,000	n.a.
		c.	4.0	1,000	350	27[o]	4,500	n.a.
		d.	5.0	800	300	25[o]	4,200	n.a.
		e.	7.5	690	210	20[o]	3,200	n.a.
		f.	10	640	180	17[o]	2,700	n.a.

n.a. = not available

[a]Rated capacity based on value of daily biogas production capacity as provided in reference. Fixed-dome digesters' capacities based on summer production values of 0.20 cubic meters of biogas per cubic meter of pit (Chen and Xiao 1979; van Buren 1979). Digesters in warmer climates could produce at a rate reported as high as 0.5 cubic meters of biogas per cubic meter of pit (Santerre 1981). In this table we assume a value of 0.2 cubic meters of biogas per cubic meter of pit.

[b]If reported in reference as number of bags, one bag of cement is assumed to weigh 50 kilograms.

[c]Includes only principal uses of steel or iron by digester; excludes steel or iron used in gas distribution pipes or valves. Thus, the fixed-dome digesters given here do not use much metal. Steel and iron are assumed to weigh 7,870 kilograms per cubic meter (Perry 1976).

[d]If reported in reference as cubic meters, one cubic meter of sand, gravel, or chipped stone is assumed to weigh 1,500 kilograms (Zimmerman and Lavine 1961); one cubic meter of cinders is assumed to weigh 720 kilograms (Perry 1976); one cubic meter of whole or hewn stone assumed to weigh 2,300 kilograms (Perry 1976).

[e]Includes: mason: 13 person-days; laborers: 23 person-days.

[f]Includes: 35 person-days for construction and 20 person-days for transporting materials. With poor soil conditions, labor could increase by 30-40 percent.

[g]Includes: mason: 14 person-days; laborers: 36 person-days.

[h]Includes: mason 30 person-days; laborers: 67.5 person-days.

[i]Includes: material preparing = 3 person-days (pd); soil digging = 3-4 pd, brick laying = 8 pd; concrete casting = 1 pd; cement coating = 10 pd; soil refilling = 1 pd; miscellaneous = 2 pd.

[j]Includes: material preparing = 3 pd; soil digging = 3-4 pd; brick laying = 2 pd; concrete casting = 1 pd; "3-in-1" soil packing = 6 pd; cement coating = 3 pd; soil refilling = 1 pd; miscellaneous = 2 pd.

[k]Steel and iron quantity based on reported use of 12.3 square meters of sheet steel (at an assumed thickness of 1.0 mm), estimated to weigh 97 kilograms. Ferrous components other than sheet steel are assumed to comprise 35 percent of total weight of gas dome, for an estimated total weight of 149 kilograms.

[l]Original data reported as 5 person-weeks; we assume a 6-day workweek. About 85 percent of labor was obtained from within the family building the digester.

Table 2. Comparison of the use of construction materials and labor (per unit of rated capacity) by 38 anaerobic digester models. Quantities are rounded to two significant digits.

[m]Reported requirement of 5.0 square meters of 12-gauge mild steel (MS) plate, estimated to weigh 100 kilograms. Ferrous components other than sheet steel are assumed to be 35 percent of total weight of dome, for an estimated total weight of 154 kilograms.

[n]Reported requirement of 68 square meters of 10-gauge MS sheet. Ferrous components other than sheet steel assumed to be 35 percent of total weight of dome, for a total weight of 2,740 kilograms.

[o]VITA (1979) reports the quantity of galvanized iron (GI) sheet required by each digester. We assume a thickness of 1.0 mm, and assume that ferrous components other than GI sheet are 35 percent of total weight of dome, for estimated total weights as follows: 2.0 m^3/day digester: 54 kilograms; 3.0 m^3/day digester: 109 kilograms; 4.0 m^3/day digester: 109 kilograms; 5.0 m^3/day digester: 127 kilograms; 7.5 m^3/day digester: 153 kilograms; and, 10.0 m^3/day digester: 173 kilograms.

[p]Data are given for unspecified floating-dome digester by VITA (1979): skilled labor = 8 hours; unskilled labor = 80 hours; welding = 12 hours.

References

[A]Senevirathne, 1981

[B]van Buren 1979

[C]Singh and Singh 1978

[D]Industrial Development Board, Sri Lanka, 1981

[E]Chen and Xiao 1974

[F]Ratasuk et al. 1979

[G]Sathianathan 1975

[H]VITA 1979

52

Table 3. Estimated life expectancies of some major components of floating-dome digesters in India (from Moulik et al. 1978).

Component	Repair frequency (years)	Replacement frequency (years)
Gas holder	4.7	8.0
Central guidepipe	n.a.	5.0
Pipelines	2.9	n.a.
Burners	n.a.	4.2

n.a. = not available

Table 4. Construction materials prorated over lifetime biogas production. This compares the requirements of two 2.8 cubic meter per day capacity digesters, with construction materials prorated over the estimated lifetime biogas production of the digesters. [Data are indexed to 10,000 cubic meters of biogas to permit comparison on an equivalent basis.]

Digester type and model	Floating-dome, KVIC[a]	Fixed-dome, Janata (D)[b]
Rated biogas production capacity (cubic meters per day)	2.8	2.8
Digester life expectancy (years)[c]	10	15
Capacity factor (percent of rated capacity)[d]	75	75
Estimated lifetime biogas production (cubic meters)	7,700	11,500
Principal construction materials (per 10,000 cubic meters of biogas)		
Bricks (number)	3,800	2,200
Cement, lime, plaster (kg)	970	430
Sand, gravel, stone (kg)	6,800	7,300
Steel, iron (kg)	200	0.0

Footnotes

a. From Sathianathan 1975.

b. From Singh and Singh 1978.

c. For illustrational purposes a shorter life expectancy is assumed for the floating-dome digester due to its use of steel components.

d. Both digesters assumed to have similar performance characteristics.

Table 5. Estimates of the annual requirement of paint and labor for maintaining the gas collector of a floating-dome digester[a].

Scale of digester	Estimated paint requirement (liters)	Estimated labor requirement (person-days)
Household-scale (2.8 m^3/day)	1	2
Community-scale (85 m^3/day)	11	27

Footnote

a. This table is for the purposes of illustration and is not based on actual data. The values of paint and labor reflect the differences in surface area of the two digesters and hence are not proportional to their gas production capacities.

Table 6. Changes in the chemical composition of U.S. dairy cattle manure after exposure to air (from Lauer 1975).

Condition of manure	Dry matter content of manure (%)	Total nitrogen (%)	Ammoniacal nitrogen as % of total nitrogen
As defecated (includes feces and urine)	11	5.7	61
Farm-fresh (about 24 hours old at time of recovery)	15	3.1	36
Farm-stored (stored in pile for indefinite period)	24	1.8	35
Farm-stored (after several days following spreading on soil)	46-85	1.5	4.5

Table 7. Daily requirements of alternative feedstock needed to produce cooking fuel for a family of five.

Feedstock	Quantity (kg/day) needed to produce[a]: 1.0 m^3 biogas/day	3.5 m^3 biogas/day	Environmental Conditions	Reference
Cattle dung (wet)	12	41	Summer (air: 30 °C)	Idnani and Varadarajan 1974
	28	98	25 °C	Rajabapaiah et al. 1979
	31	110	Winter (air: 14 °C)	Idnani and Varadarajan 1974
Grass (dried)	1.6	5.6	none given	van Buren 1979
Maize straw (dried)	1.2	4.3	none given	Singh 1974
Night soil	14	49	none given	Srinivasan 1978
Pig manure	13	44	none given	Srinivasan 1978
Poultry dung	16	56	none given	Srinivasan 1978
Rice husks (dried)	1.6	5.6	none given	van Buren 1979

Assumptions

1. Family size: five persons.[b]
2. Quantity of biogas required for cooking by family of five persons[c]:
   1.0 cubic meters of biogas per day (Garg 1978; van Buren 1979)
   3.5 cubic meters of biogas per day (Singh 1974)

Footnotes

a. Two values for feedstock requirements are estimated to correspond with the range of biogas cooking fuel requirements given in the literature. Assumptions about animal size or health status, moisture content of dung, and other factors affecting the feedstock-biogas relationship are seldom reported.
b. This is a common reference point used in the literature; no other assumptions are given (e.g. age of members, etc.).
c. Literature cited make no reference to amount of food cooked, or efficiency of cooking methods or appliances.

Table 8. Estimated labor requirements for operating a household-scale anaerobic digester in India (from French 1979).

Activity	Labor requirements	Comment
Collecting dung (80 kg)	0 net hours per day	Activity assumed to be equal to time formerly spent collecting fuel
Hauling water (80 kg)	0.5 hours per day	
Mixing inputs and operating plant	0.75 hours per day	
Distributing sludge (140 kg)	0.75 hours per day	Total weight of inputs times 0.9
TOTAL	2.0 hours per day	

Table 9. Estimated quantities of manures and commercial fertilizers needed to supply one kilogram of nitrogen[a].

Source of nitrogen	Quantity required per kilogram of nitrogen (kg)
Ammonium phosphate	9
Ammonium superphosphate	33
Ammonium sulphate	5
Urea	2
Cattle dung[b]	340
Cattle dung (dried to 20% of fresh weight)	130
Anaerobically digested cattle dung sludge (wet)	680
Anaerobically digested cattle dung sludge (dried to 10 % of wet weight)	80

Footnotes

a. There is evidence that the nitrogen present in organic manures is only 25 percent as available to crops as the nitrogen present in inorganic fertilizers (Idnani and Varadarajan 1974). The present table assumes no differences in nitrogen availability between organic and inorganic manures.

b. Nitrogen values of manures are based on Rajabapaiah et al. 1979.

Table 10. Specifications plate of the gross resource requirements for a 2.8 cubic meter fixed-dome Janata digester.

Digester:	Fixed-dome, Janata (Singh and Singh 1978)
Rated capacity:	2.8 cubic meters of biogas per day
Performance (assumed)[a]:	
a. Life expectancy	15 years
b. Capacity factor	75 percent
c. Quantity of fuel produced during lifetime	11,500 cubic meters of biogas

	Digester construction (total resources)		Digester construction (per m^3 of rated capacity)		Digester operation (per m^3 of biogas produced)		Lifetime resource requirements at assumed performance levels (per 10,000 m^3 of biogas)	
	Local	National	Local	National	Local	National	Local	National
PHYSICAL RESOURCES (principal)								
a. Bricks (units)		2,500		890				2,200
b. Cement, lime, plaster (kg)		500		180				440
c. Sand, gravel, stone, cinders, etc. (kg)	8,400		3,000				7,300	
d. Water[b] (kg)	250 •		89 •				220 •	
Other physical resources[c]								
a. Cattle dung[d] (kg)					28 •		28,000 •	
b. Water (kg)					28 •		28,000 •	
SOCIAL RESOURCES								
Labor[e,f] (person-days)								
a. Skilled	17 •	4 •	6 •	1 •			15 •	3.5 •
b. Unskilled	65 •		23 •		0.15 •		1,600 •	
Extensive measures								
New job types (+,0)	+	0			+	0		
Village organization needed (low, medium, high)	low				low			
Sophistication of jobs (low, medium, high)	high	low			medium	low		
Monetary economy (low, medium, high)	low				low			
Cultural taboos					potential			
ENVIRONMENTAL RESOURCES								
Land (m^2)	25 •							
Extensive measures								
Temperature					> 20 °C			

29

Table 10. Specifications plate of the gross resource requirements for a 2.8 cubic meter fixed-dome Janata digester

OTHER MEASURES

Fuel predictability: anaerobic digesters, compared to other small-scale energy technologies, score "1" on a scale of 1 (predictable) to 3 (stochastic), that is, anaerobic digestion systems are less subject to variations in output than, say, windmills.

Siting flexibility: anaerobic digesters, compared to other small-scale energy technologies, score "1" on a scale of 1 (flexible siting) to 3 (special requirements).

Fuel density: biogas scores a "3" for fuel density, on a scale of 1 (high density) to 3 (low density). The energy density of biogas is between 0.019 and 0.026 MJ/liter (National Academy of Sciences 1977). Anaerobic digestion is thus more suitable for stationary technologies than for mobile technologies. Digester sludge (a byproduct of digestion and a valuable fertilizer and soil conditioner) scores a "3" in terms of fertilizer density if in the wet state, and a "2" if in the dried state, on a scale of 1 (high density) to 3 (low density).

Footnotes

* = estimated value

a. Values assumed for digester performance are for illustrational purposes only, and are not based on actual performance data, which are unavailable.

b. Original source (Singh and Singh 1978) does not provide data on water consumption. Water is a component of concrete, and water is assumed here be required at a weight 0.5 times the weight of cement.

c. Refer to Table 1 for information on energy embodied in construction materials. These data are not presented here to avoid double-counting (which would occur if both the materials and the resources embodied in the materials were included above).

d. Cattle dung is chosen here as the organic feedstock for illustrational purposes.

e. Labor for construction is reported as 43 person-days (Singh and Singh 1978). We have added to this 22 person-days to account for labor required to procure local construction materials. We add an additional 22 person-days for constructing components of the biogas distribution, feedstock and residue management subsystems, for a total labor requirement of 87 person-days. We have assumed that 75 percent of this labor is unskilled and available from local sources, 20 percent is skilled and available from local sources, and 5 percent is skilled and unavailable locally.

f. Labor for operating a digester is assumed to be required in the following two-year cycle (i.e. emptying, major maintenance, and refilling of the digester is required every other year): a. Initial filling of digester: 5 person-days; b. Daily operations: 3 hours per day (gross), assumed to be 0.3 person-days per day for 23 months (207 person-days); c. Emptying, maintenance: 15 person-days; Total: 230 person-days over two-year period; [230 person-days x (15 years/2 years) = 1,700 person-days for lifetime of digester; 1,700 x (10,000 m^3 / 11,500 m^3) = 1,500 person-days per 10,000 m^3 of biogas; 1,500 person-days / 10,000 cubic meters of biogas = 0.15 person-days per m^3 of biogas; Note: These labor estimates exlude extension workers or similar persons working in an advisory capacity. The estimates presented here are educated guesses, and are for illustrational purposes only.]

63