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Biogas Plants in Animal Husbandry

By: Uli Werner, Ulrich Stohr, and Nicolai Hees

Uli Werner/Ulrich Stöhr/Nicolai Hees

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Aus der
Arbeit von
gate
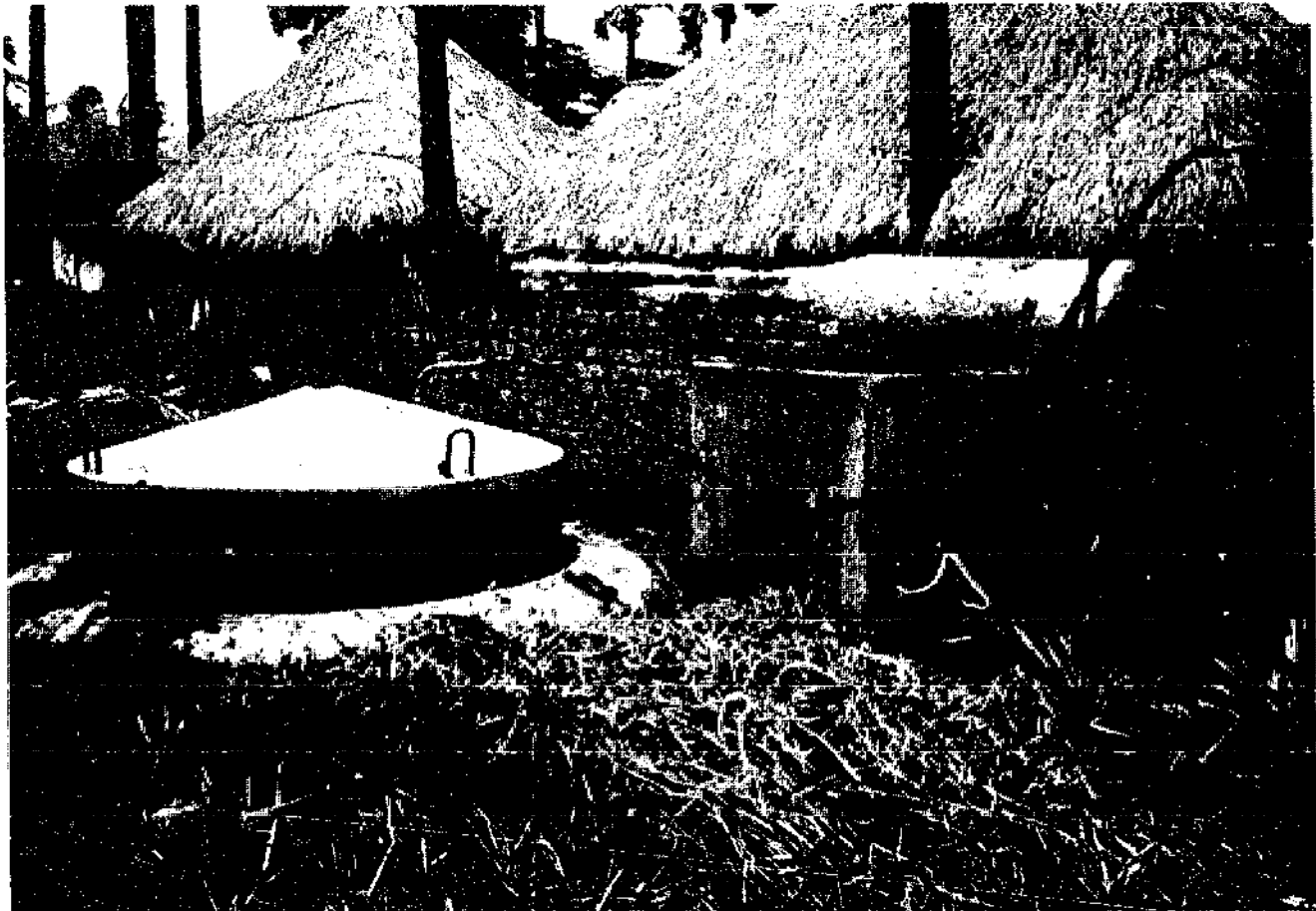
Vieweg

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Deutsches Zentrum für Entwicklungstechnologien – GATE – stands for German Appropriate Technology Exchange. It was founded in 1978 as a special division of the Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH. GATE is a centre for the dissemination and promotion of appropriate technologies for developing countries. GATE defines „Appropriate technologies" as those which are suitable and acceptable in the light of economic, social and cultural criteria. They should contribute to socio-economic development whilst ensuring optimal utilization of resources and minimal detriment to the environment. Depending on the case at hand a traditional, intermediate or highly-developed can be the „appropriate" one. GATE focusses its work on four key areas:
– *Technology Exchange:* Collecting, processing and disseminating information on technologies appropriate to the needs of the developing countries; ascertaining the technological requirements of Third World countries; support in the form of personnel, material and equipment to promote the development and adaptation of technologies for developing countries.
– *Research and Development:* Conducting and/or promoting research and development work in appropriate technologies.
– *Cooperation in Technological Development:* Cooperation in the form of joint projects with relevant institutions in developing countries and in the Federal Republic of Germany.
– *Environmental Protection:* The growing importance of ecology and environmental protection require better coordination and harmonization of projects. In order to tackle these tasks more effectively, a coordination center was set up within GATE in 1985.
GATE has entered into cooperation agreements with a number of technology centres in Third World countries.
GATE offers a free information service on appropriate technologies for all public and private development institutions in developing countries, dealing with the development, adaptation, introduction and application of technologies.

Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH

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The GTZ activities encompass:
appraisal, technical planning, control and supervision of technical cooperation projects commissioned by the Government of the Federal Republic or by other authorities
providing an advisory service to other agencies also working on development projects
the recruitment, selection, briefing, assignment, administration of expert personnel and their welfare and technical backstopping during their period of assignment
– provision of materials and equipment for projects, planning work, selection, purchasing and shipment to the developing countries
– management of all financial obligations to the partner-country.

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Biogas Plants in Animal Husbandry

A Practical Guide

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The Authors:
Uli Werner, a graduate in civil engineering, was born in 1950 and is presently resident in Berlin. Between 1976 and 1980 he was one of the founders and pioneers of the interdisciplinary project group for appropriate technology (IPAT) at Berlin Technical University. For the following seven years (1980–1987) he worked for OEKOTOP GmbH and as a consultant for the GATE/GTZ biogas dissemination programme. Since 1987 he has worked as a freelance consultant for Third World countries in the fields of biogas, regenerative energy technologies and appropriate technologies.

Nicolai Hees, born 1954 in Hanau, West Germany, studied agricultural science in Gießen and completed a postgraduate programme on energy management at the Technical University of Berlin. Worked in Burkina Faso 1982–1983. Since 1984 staff member of OEKOTOP GmbH in Berlin. Specialized in anaerobic digestion. He has worked on various technical cooperation projects in Africa and Latin America.

Ulrich Stöhr-Grabowski, economist, born 1949. Worked in Somalia for the German Red Cross 1980–1981. Scientific assistant at the Technical University of Berlin from 1981–1982. Staff member of OEKOTOP GmbH from 1983–1988. Specialized in the use of renewable energy. Since 1988 socio-economical advisor for the biogas extension programme in Thailand.

Drawings: Kirsten Pfeifer

The author's opinion does not necessarily represent the view of the publisher.

Biogas technology has in the meantime been generally accepted and widely used. The number of constructed and operable plants, especially in countries of the Third World, has already reached the hundred thousands.

The use of simple biogas plants for rural regions in developing countries – the primary subject matter of this book – is complex; it is also worthwhile to study the application, planning, construction and surroundings of this technology. Anyone dealing with biogas plants in practice knows that only a well planned, carefully constructed and thus operable biogas plant which meets its purpose is an efficient biogas plant.

The purpose of this book is to be of assistance to persons concerned with planning, practical application and to extension workers. It shall serve as

    information on the possibilities and application conditions of biogas technology
    assistance for deciding in favor of and planning plant construction and expansion
    a reference book on practical experiences and information in detail.

Deutsches Zentrum für Entwicklungstechnologien

Contents

Foreword

Biogas plants have become something of a permanent fixture in Technical Cooperation between the Federal Republic of Germany and partners in developing countries. Dating back to 1977, the first such projects were incorporated into cooperative efforts with Indian and Ethiopian organizations. At about the same time, the first GTZ project dealing solely with the transfer of biogas technology and the construction of biogas plants was launched in Cameroon.

In the meantime, GTZ has assisted in building and commissioning several hundred biogas plants in Asia, Africa, South and Central America. While most of the systms, in question are on a small scale intended to supply family farms with energy and organic fertilizer, some large-scale systems with the capacity to generate more than 100 m^3 of biogas daily have been installed on large stock farms and agroindustrial estates.

In general, biogas technology is for rural areas. In addition to generating energy, biogas systems help stimulate ecologically beneficial closed-loop systems in the agricultural sector while serving to improve soil quality and promote progress in animal husbandry. Consequently, the promotion of biogas technology is regarded as an integral part of technical cooperation in rural areas and, hence, as a key sector of development cooperation on the part of the Federal Republic of Germany.

Within the GTZ, biogas activities center on
— the Biogas Extension Program (GATE), with interdisciplinary teams of extension officers presently working in four different countries:

— the Special Energy Program (Mineral and Energy Resources Division), with rural energy-supply projects now ongoing in ten countries, and
— projects engaged in by Division 14 (animal production, animal health and fisheries), within which the importance of biogas technology as a flanking measure in animal husbandry is steadily increasing.

By concentrating the engineering and operational experience gained in numerous biogas projects, this handbook is intended to serve project practicians and advisors as a valuable practical guideline with regard to technical, agricultural and socioeconomic aspects.

Deutsche Gesellschaft für Technische
Zusammenarbeit (GTZ) GmbH

Authors' Foreword

Biogas plants constitute a widely disseminated branch of technology that came into use more than 30 years ago in Third World countries. There are hundreds of thousands of simple biogas plants now in operation, and each one of them helps improve the living and working conditions of people in rural areas.

While this guide deals only with biogas systems of simple design, the technology is nonetheless sufficiently complex and rewarding to warrant one's close attention to its proper application, planning and construction. The only good biogas system is

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a well-planned, carefully executed and properly functioning one that fulfills its purpose.

This guide addresses the planners and providers of stock-farming and agricultural-extension services in developing countries. It is intended to serve as:

— a source of information on the potentials of and prerequisites for biogas technology,

— a decision-making and planning aid for the construction and dissemination of biogas plants

— a book of reference for information on practical experience and detailed data.

While consulting experts, extension officers and advisors with little experience in biogas technology will find this guideline useful as an initial source of information, biogas practicians can use it as a hands-on manual. The tables and engineering drawings contained herein provide standard values for practical application. They were compiled from numerous extraneous and proprietary works of reference and then modified as necessary for practical use. The informational content draws chiefly on the latest know-how and experience of numerous associates involved in the various biogas projects of the GTZ Special Energy Program and the GATE/GTZ Biogas Extension Program, of L. Sasse and a great many Third World colleagues and, last but not least, OEKOTOP's own project experience.

We wish every success to all users of this guide. Feedback in the form of suggestions and criticism is gratefully welcomed.

The OEKOTOP Authors

1. An Introduction to Biogas Technology

Biogas technology

. . . is a modern, ecology-oriented form of appropriate technology based on the decomposition of organic materials by putrefactive bacteria at suitable, stable temperatures. A combustible mixture of methane and carbon dioxide, commonly referred to as biogas, develops under air exclusion (leaving behind digested slurry) in the digester — the heart of any biogas plant.
To ensure continuous gas production, the biogas plant must be fed daily with an ample supply of substrate, preferably in liquid and chopped or crushed form. The slurry is fed into the digester by way of the mixing pit. If possible, the mixing pit should be directly connected to the livestock housing by a manure gutter. Suitable substrates include:
– dung from cattle, pigs, chickens, etc.,
– green plants and plant waste,
– agroindustrial waste and wastewater.
Wood and ligneous substances are unsuitable.

Fig. 1.1: A typical biogas-system configuration (Source: OEKOTOP)
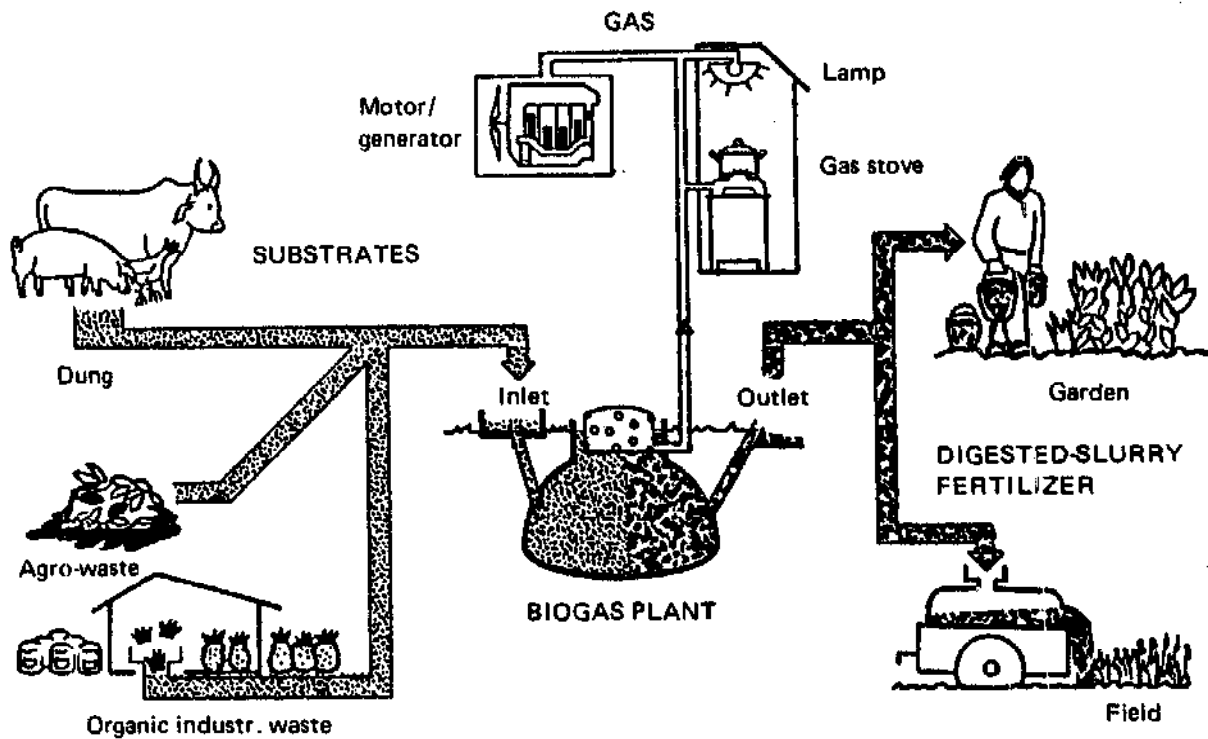
Suitable digesting temperature:	20–35 °C
Retention time:	40–100 days
Biogas energy content:	6 kWh/m³ = 0.6 l diesel fuel
Biogas generation:	0.3–0.5 m³ gas/m³ digester volume × day
1 cow yields:	9–15 kg dung/day = 0.4 m³ gas/day
1 pig yields:	2–3 kg dung/day = 0.15 m³ gas/day
Gas requirement for cooking:	0.1–0.3 m³/person
for 1 lamp:	0.1–0.15 m³/h
for engines:	0.6 m³/kWh

A simple 8–10 m³ biogas plant produces 1.5–2 m³ and 100 l digested-slurry fertilizer per day on dung from 3–5 head of cattle or 8–12 pigs. With that much biogas, a 6–8-person family can:

– cook 2–3 meals or

– operate one refigerator all day and two lamps for 3 hours or

– operate a 3 kW motor generator for 1 hour.

Of the many alternative forms of agricultural biogas systems, two basic types have gained widespread acceptance by reason of their time-tested reliability and propagability:

– floating-drum plants with a floating metal gasholder,

– fixed-dome plants with gas storage according to the displacement principle.

The main difference between the two is that the biogas generated in a fixed-dome plant collects in the domed roof of the digester, while that produced in a floating-drum plant collects in a metal gasholder. The gasholder, the purpose of which is to cover peak demand, is directly hooked up to the consumers (kitchen, living quarters, refrigerator, motor generator, . . .) by way of pipes.

Plant construction is effected with as much local material as possible, i.e.:

– bricks, rocks, sand, cement for the digester,

– metal or plastic tubes for the gas pipes,

– metal for the gasholder,

– gas valves, fittings and appliances.

Target groups and applications

The prime field of application for biogas plants is family farms, particularly those engaging in animal husbandry. Also, biogas plants are a proven successful means of disposal for wastewater and organic waste. Differentiation is made between the following groups of users:

– Small and medium-sized farms equipped with family-size plants (6–25 m³ digester) use biogas for cooking and lighting. The installation of a biogas plant usually goes hand in hand with a transition to either overnight stabling or zero grazing. The modified stabling, coupled with the more intensive care given to the animals, improves the quality of animal husbandry as an inherent advantage of biogas technology.

– Specialized stock-farming operations involving the medium to large-scale production of cattle, pigs and/or poultry can use medium-to-large biogas systems with digester volumes ranging from 50 m³ upward. The resultant safe disposal of fresh manure is a real contribution toward environmental protection, particularly with regard to the prevention of water pollution. Moreover, that contribution is rewarding for the farmer, too, since the biogas constitutes an autonomous source of energy for production processes.

– For agroindustrial estates and slaughterhouses, the pro-biogas arguments are similar to those mentioned above in connection

with stock farms: safe disposal of potentially hazardous solid and liquid waste materials, coupled with a private, independent source of energy for generating electricity, powering coolers, etc.

- Biogas plants in schools, hospitals and other public institutions provide a hygienic means of toilet/kitchen-waste disposal and a low-cost alternative source of energy. Schools in particular serve as multipliers for the dissemination of information on biogas.

Gas appliances

A number of Third World manufacturers offer specially designed cooking burners and lamps that operate on biogas. Standard commercial cookers and lamps can also be converted to run on biogas.

Photo 1: Floating-drum plant with slurry storage pit in India (Source: OEKOTOP)

Photo 2: Fixed-dome plant with displacement pit in the foreground, entry hatch at center left, and inlet mixing pit at rear (Source: OEKOTOP)

Diesels and spark-ignition engines can be fueled with biogas following proper modification; diesel engines prefer a mixture of biogas and diesel fuel. Biogas-fueled refrigerators, though not very efficient, are attractive alternatives for hospitals, schools and restaurants without electrification.

Slurry utilization

The digested slurry from biogas plants is a valuable organic fertilizer, since most of the main nutrients (N, P, K) are preserved. In areas where regular fertilizing is uncommon, the use of digested slurry for that purpose requires intensive counseling of the farmer. Biogas technology can play an important role in self-sustaining ecofarming.

The advantages of biogas technology

. . . for the user consist chiefly of direct monetary returns, less work and various qualitative benefits.

The monetary returns consist mainly of:
— savings on kerosene, diesel fuel, bottled gas and, possibly, wood or charcoal,
— an additional energy supply for commercial activities,
— savings on chemical fertilizers and/or additional income from higher agricultural yields.

The qualitative benefits are:
— easier, cleaner cooking and better hygiene,
— better lighting during the evening hours,
— energy independence,
— improved stock-farming practice,
— good soil structure thanks to fertilization with digested sludge.

The regional and overall domestic significance derives from the following merits and aspects:

— development of a reliable, decentralized source of energy operated and monitored by the users themselves,
— less local deforestation,
— improved conditions of agricultural production,
— more work and income for local craftsmen,
— infrastructural development,
— expanded indigenous technological knowhow.

While the absolute figures corresponding to the above effects may often be marginal as compared to the overall economy, they nonetheless have a noticeable impact within the project region.

Cost of construction, amortization

As a rule, it costs DM 1000 or more to install a masonry biogas plant, including all peripheral equipment, i.e. improved stabling, gas appliances, piping, etc. A favorable payback period of less than 5 years can be anticipated for such an investment, if the biogas is used in place of a commercial energy source like kerosene or firewood, but not if it is used as a substitute for "free" firewood.

Dissemination of biogas technology

Thanks to the broad scale of potential uses for biogas, in conjunction with an increasingly advanced state of technical development, numerous developing countries are intensively promoting the dissemination of biogas plants. The undisputed leaders are the PR China (4.5 million plants), India (200 000 plants) and Brazil (10 000 plants). Other countries also have launched biogas dissemination programs with some or all of the following components:
— development of appropriate appliances and plants,

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- establishment of technology and advisory-service centers,
- continuous support for the users,
- training of biogas practicians,
- advertising and promotional activities,
- assistance for private craftsmen,
- provision of financing assistance.

Criteria for the utilization of biogas technology

Building a biogas plant is not the kind of project that can be taken care of "on the side" by anyone, least of all by a future user with no experience in biogas technology. The finished plant would probably turn out to be poorly planned, too expensive and, at best, marginally functionable – all of which would disappoint the user and spoil the prospects for the construction of additional plants. Consequently, the following rules of thumb should be observed:

– There are workable alternatives to biogas technology:

Regarding energy: energy-saving cookstoves, afforestation, wind/solar energy, small-scale hydropower, etc.; better access to commercial energy supplies

Regarding fertilization: spreading or composting of fresh dung

Regarding animal husbandry: pasturing instead of stabling in combination with a biogas plant.

Any decision in favor of or against the installation of a biogas plant should be based on due consideration of how it compares to other alternatives according to technical, economic, ecological and socioeconomic criteria.

– Both the available supply of substrate and the energy requirements must be accurately calculated, because the biogas plant would not be worth the effort if its energy yield did not cover a substantial share of the energy requirements.

– The system must be properly built in order to minimize the maintenance & repair effort.

– Siting alternatives must be painstakingly compared, and only a really suitable location should be selected for the biogas plant.

The financial means of the plant's user must not be overextended (risk of excessive indebtedness).

2. A Planning Guide

2.1 Introduction

This guide to planning is intended to serve agricultural extension officers as a comprehensive tool for arriving at decisions concerning the suitability of locations for family-size biogas plants. The essential siting conditions capable of influencing the decision for or against a biogas plant are covered (cf. figure 2.1 for a summary survey). The detailed planning outline (table 2.1) has a "data" column for entering the pertinent information and a "rating" column for noting the results of evaluation

Evaluation criteria

+ Siting condition favorable
o Siting condition unfavorable, but
    a) compensable by project activities,
    b) not serious enough to cause ultimate failure,
  - Siting condition not satisfied / not satisfiable

Information on how to obtain and evaluate the individual data can be found in the corresponding chapters of this manual by following the pointers provided in the "reference" column.

Despite its detailed nature, this planning guide is, as intended, nothing more than a framework within which the extension officer should proceed to conduct a careful investigation and give due consideration, however subjectively, to the individual conditions in order to arrive at a locally practical solution. By no means is this planning guide intended to relieve the agricultural extension officer of his responsibility to thoroughly familiarize himself with the on-the-spot situation and to judge the overall value of a given location on the basis of the knowledge thus gained.

Fig. 2.1: Biogas planning modules
(Source: OEKOTOP)

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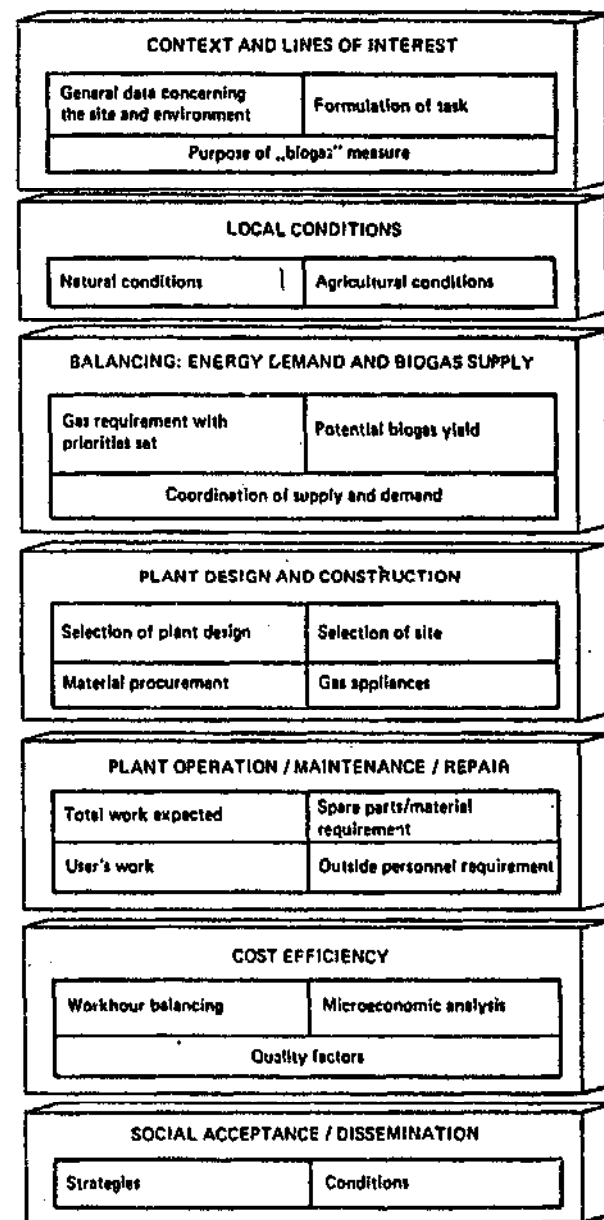
2.2 Detailed Planning Guide

Table 2.1: Detailed planning guide for biogas plants

Item	Reference	Data	Rating
0. Initial situation			
Addresses/project characterization			
Plant acronym:		. . . .	
Address of operator/customer:		. . . .	
Place/region/country:		. . . .	
Indigenous proj. org./executing org.:		. . . .	
Extension officer/advisor:		. . . .	
General user data			
Household structure and no. of persons:		. . . .	
User's economic situation:	•	. . . .	
Animals: kind, quantity, housing:		. . . .	
Crops: types, areas, manner of cultivation:		. . . .	
Non-agricultural activity:		. . . .	
Household/farm income:		. . . .	
Cultural and social characteristics of user:		. . . .	
Problems leading to the "biogas" approach			
Energy-supply bottlenecks:		. . . .	
Workload for prior source of energy:		. . . .	
Poor soil structure/yields:		. . . .	
Erosion/deforestation:		. . . .	
Poor hygiene . . ., other factors:		. . . .	
Objectives of the measure "biogas plant"			
User interests:		. . . .	
Project interests:		. . . .	
Other interests:		. . . .	
1. Natural / Agricultural conditions			
Natural conditions	Chapter 3.1		
Mean annual temperature:		. . . .	
Seasonal fluctuations:		. . . .	
Diurnal variation:		. . . .	
Rating:		. . . .	+ o −
Subsoil	Chapter 3.1		
Type of soil:		. . . .	
Groundwater table, potable water catchment area:		. . . .	
Rating:			+ o −

Ratings: + Siting condition favorable
o Siting condition unfavorable but compensable and/or not too serious
− Siting condition not satisfied / not satisfiable

Item	Reference	Data	Rating
Water conditions	Chapter 3.1		
Climate zone:	Table 3.1	. . . .	
Annual precipitation:		. . . .	
Dry season (months):		. . . .	
Distance to source of water:		. . . .	
Rating:			+ o –
Livestock inventory, useful for biogas	Chapter 3.2/3.3		
production		. . . .	
Animals: kind and quantity:		. . . .	
Type and purpose of housing:		. . . .	
Use of dung:		. . . .	
Persons responsible for animals:		. . . .	
Rating:			+ o –
Vegetable waste, useful for biogas production	Chapter 3.2/3.3		
Types and quantities:		. . . .	
Prior use:		. . . .	
Rating:			+ o –
Fertilization	Chapter 3.4		
Customary types and quantities of fertilizer/areas fertilized:		. . . .	
Organic fertilizer familiar/in use:		. . . .	
Rating:			+ o –
Potential sites for biogas plant	Chapter 3.3		
Combined stabling/biogas plant possible:		. . . .	
Distance between biogas plant and livestock housing:		. . . .	
Distance between biogas plant and place of gas consumption:		. . . .	
Rating:			+ o –
Overall rating 1			+ o –

2. Balancing the energy demand with the biogas production	Chapter 4		
Prior energy supply	Chapter 4		
Uses, source of energy, consumption:		. . . .	
Anticipated biogas demand (kWh/day or l/d)	Chapter 5.5.3		
for cooking:	Table 5.17	. . . .	
for lighting:	Table 5.20	. . . .	
for cooling:	Table 5.22	. . . .	
for engines:	Chapter 5.5.4	. . . .	
. . . .			
Total gas demand	Chapter 4.1		
a) percentage that *must* be provided by the biogas plant:		. . . .	
b) desired demand coverage:		. . . .	

Ratings: + Siting condition favorable
o Siting condition unfavorable but compensable and/or not too serious
– Siting condition not satisfied / not satisfiable

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Item	Reference	Data	Rating
Available biomass (kg/d) and potential gas production (l/d)	Chapter 3/4		
from animal husbandry	Table 3.2	. . . .	
. . . pigs:	Table 3.5	. . . .	
. . . poultry:	Table 4.3	. . . .	
. . . cattle:	Figure 5.2	. . . .	
. . . .			
Night soil	Table 3.2	. . . .	
Vegetable waste (quantities and potential gas yield)	Table 3.3		
1.	Table 3.5	. . . .	
2.			
Totals: biomass and potential gas production	Chapter 4.2		
a) easy to procure:		. . . .	
b) less easy to procure:		. . . .	
Balancing	Chapter 4.4		
Gas production clearly greater than gas			
demand = positive rating (+)		. . . .	
Gas demand larger than gas production			
= negative rating (–); but review of results in order regarding:		. . . .	
a) possible reduction of gas demand by the following measures		. . . .	
. . . .			
b) possible increase in biogas production by the following measures		. . . .	
. . . .			
If the measures take hold:		. . . .	
= qualified positive rating for the plant location (o)			
If the measures do not take hold:		. . . .	
= site rating remains negative (–)			
Overall rating 2			+ o –

3. Plant Design and Construction	Chapter 5		
Selection of plant design	Chapter 5.3		
Locally customary type of plant:		. . . .	
Arguments in favor of floating-drum plant:	Chapter 5.3.1	. . . .	
Arguments in favor of fixed-dome plant:	Chapter 5.3.2	. . . .	
Arguments in favor of other plant(s):	Chapter 5.3.3	. . . .	
Type of plant chosen:		. . . .	
Selection of site		. . . .	

Ratings: + Siting condition favorable
          o Siting condition unfavorable but compensable and/or not too serious
          – Siting condition not satisfied / not satisfiable

Item	Reference	Data	Rating
Availability of building materials			
Bricks/blocks/stone:		. . . .	
Cement:		. . . .	
Metal:		. . . .	
Sand:		. . . .	
Piping/fittings:		. . . .	
Miscellaneous:		. . . .	
Availability of gas appliances			
Cookers:		. . . .	
Lamps:		. . . .	
. . . .		. . . .	
. . . .		. . . .	
Overall rating 3			+ o –

4. Plant operation / maintenance / repair	Chapter 7		
Assessment of plant operation	Chapter 7.1		
Incidental work:	Chapter 7.2	. . . .	
Work expenditure in h:		. . . .	
Persons responsible:		. . . .	
Rating with regard to anticipated implementation:			+ o –
Plant maintenance	Chapter 7.3		
Maintenance-intensive components:		. . . .	
Maintenance work by user:	Table 7.2	. . . .	
Maintenance work by external assistance:		. . . .	
Rating with regard to anticipated implementation:			+ o –
Plant repair	Chapter 7.4		
Components liable to need repair:		. . . .	
Repairs that can be made by the user:		. . . .	
Repairs requiring external assistance:		. . . .	
Requisite materials and spare parts:		. . . .	
Rating with regard to expected repair services:			+ o –
Overall rating 4			+ o –

5. Economic analysis	Chapter 8		
Time-expenditure accounting	Chapter 8.2		
Time saved with biogas plant	Table 8.1	. . . .	
Time lost due to biogas plant		. . . .	
Rating:			+ o –

Ratings: + Siting condition favorable
o Siting condition unfavorable but compensable and/or not too serious
– Siting condition not satisfied / not satisfiable

Item	Reference	Data	Rating
Microeconomic analysis	Chapter 8.3		
Initial investment:	Table 8.2	. . . .	
Cost of operation/maintenance/repair:		. . . .	
Return on investment:energy, fertilizer, otherwise:		. . . .	
Payback time (static):	Table 8.3	. . . .	
Productiveness (static):		. . . .	
Rating:			+ o −
Quality factors, useful socioeconomic effects and costs	Chapter 8.5		
Useful effects: hygiene, autonomous energy, better			
lighting, better working conditions, prestige:		. . . .	
Drawbacks: need to handle night soil, negative social impact:		. . . .	
Rating:			+ o −
Overall rating 5			+ o −

6. Social acceptance and potential for dissemination	Chapter 9		

Item	Reference	Data	Rating
Anticipated acceptance	Chapter 9.1		
Participation in planning and construction:		. . . .	
Integration into agricultural setting:		. . . .	
Integration into household:		. . . .	
Sociocultural acceptance:		. . . .	
Rating:			+ o −
Establishing a dessemination strategy	Chapter 9.2		
Conditions for and chances of the protessional-			
craftsman approach:		. . . .	+ o −
Conditions for and chances of the self-help			
oriented approach:		. . . .	+ o −
General conditions for dissemination			
Project-executing organzization and its staffing:	Chapter 9.3	. . . .	
organizational structure:		. . . .	
interest and prior experience in biogas technology:		. . . .	
Regional infrastructure for transportation and			
communication:		. . . .	
material procurement:		. . . .	
Craftsman involvement, i.e.	Chapter 9.4		
which activities:		. . . .	
minimum qualifications:		. . . .	
tools and machines:		. . . .	
Training for engineers, craftsman and users:	Chapter 9.5	. . . .	

Ratings: + Siting condition favorable
           o Siting condition unfavorable but compensable and/or not too serious
           − Siting condition not satisfied / not satisfiable

Item	Reference	Data	Rating
Proprietary capital, subsidy/credit requirement on the part of	Chapter 9.6		
user:		. . . .	
craftsmen:		. . . .	
Rating:		. . . .	+ o −
Overall rating 6		. . . .	+ o −

7. Summarization

Siting conditions	No.	Rating
Natural/agricultural conditions	1	+ o −
Balancing the energy demand and the biogas production	2	+ o −
Plant design and construction	3	+ o −
Plant operation/maintenance/repair	4	+ o −
Economic analysis	5	+ o −
Social acceptance and potential for dissemination	6	+ o −
Overall rating of siting conditions		+ o −

Ratings: + Siting condition favorable
o Siting condition unfavorable but compensable and/or not too serious
− Siting condition not satisfied / not satisfiable

Following assessment as in table 2.1, the biogas-plant site in question can only be regarded as suitable, if most of the siting factors have a favorable (+) rating. This applies in particularly to item 2, the positive energy balance, meaning that the potential biogas production must cover the gas demand.

If the favorable and unfavorable ratings are fairly well balanced, the more decisive factors should be re-evaluated to determine the extent to which supplementary measures could provide the missing conditions for building and operating a biogas plant despite some reservations but without injustifiable effort. Then, if the overall evaluation does not swing toward the positive side, the plant should not be built. If the site is given a favorable rating, further planning hints can be taken from the following checklist.

2.3 Checklist for Building a Biogas Plant

1. Finishing the planning, i.e. site evaluation, determination of energy demand and biomass supply/biogas yield, plant sizing, selection of plant design, how and where to use the biogas, etc., all in accordance with the above planning guide.

2. Stipulate the plant's location and elaborate a site plan, including all buildings, gas pipes, gas appliances and fields to be fertilized with digested slurry.

3. Draft a technical drawing showing all plant components, i.e. mixing pit, connection to stabling, inlet/outlet, digester, gasholder, gas pipes, slurry storage.

4. Preparation of material/personnel require-
ments list and procurement of materials
needed for the chosen plant:
— bricks/stones/blocks for walls and founda-
tion
— sand, gravel
— cement/lime
— inlet/outlet pipes
— metal parts (sheet metal, angle irons, etc.)
— gas pipes and fittings
— paint and sealants
— gas appliances
— tools
— mason and helper
— unskilled labor
— workshops for metal (gasholder) and pipe
installation.

5. Material/personnel assignment planning,
i.e. procedural planning and execution of:

— excavation
— foundation slab
— digester masonry
— gasholder
— rendering and sealing the masonry
— mixing pit — slurry storage pit
— drying out the plant
— installing the gas pipe
— acceptance inspection.

6. Regular building supervision.

7. Commissioning
— functional inspection of the biogas plant
and its components
— starting the plant

8. Filling the plant.

9. Training the user.

3. The Agricultural Setting

3.1 Natural Parameters for Biogas Plants of Simple Design

Climate zones

A minimum temperature of 15 °C is required for anaerobic fermentation of organic material (cf. chapter 5.1). Since simple biogas plants are unheated, they can only be used in climatic zones in which the minimum temperature is not fallen short of for any substantial length of time. In general, this is true of the area located between the two tropics, i.e. in the geographic region referred to as the "Tropics".

In the climatic sense, however, the Tropics are inhomogeneous, containing various climatic zones with their own typical forms of vegetation and agricultural practices. Pro-

ceeding on that basis, it may be said that a particular zone does or does not qualify as a "biogas zone" (cf. table 3.1).

With the exception of subtropical arid regions (deserts and semideserts), all tropical climates are characterized by:

- increasingly small diurnal and seasonal temperature variation in the direction of the equator,
- decreasing annual rainfall and number of humid months with increasing distance from the equator.

This basic zonal breakdown, though, is altered in several ways by other climatic factors such as wind, elevation and ocean currents. Consequently, the climatic zones serve only as a basis for rough orientation with regard to the climatic evaluation of potential sites for biogas plants. The locally

Fig. 3.1: Global 15 °C isotherms for January and July, indicating the biogas-conducive temperature zone (Source: OEKOTOP)
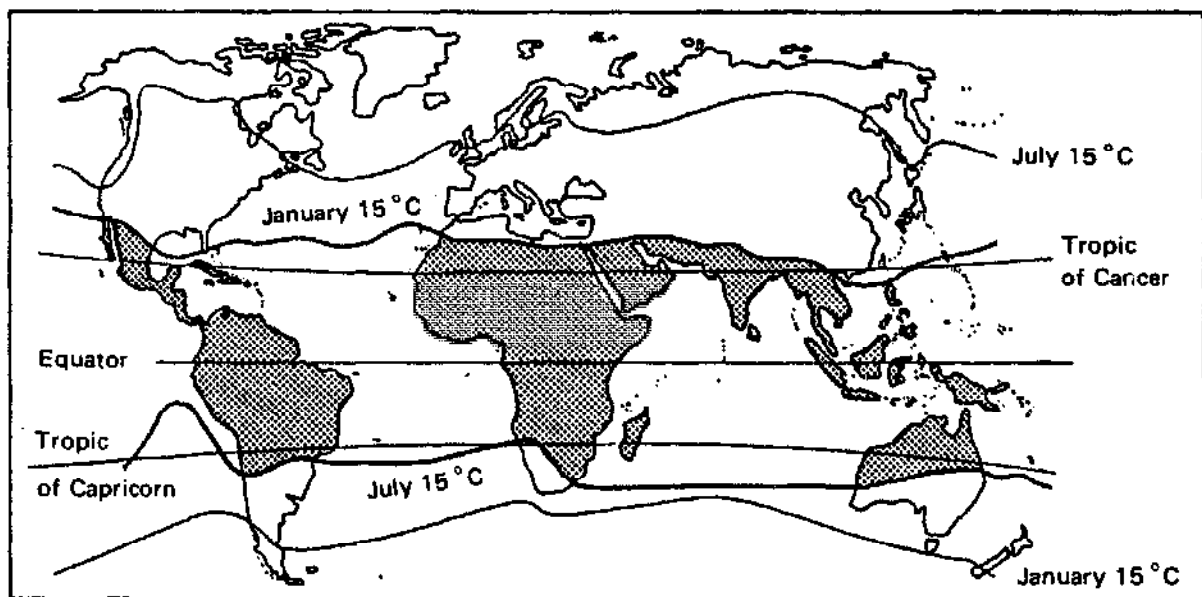
Table 3.1: Climatic zones and their suitability for biogas plants (Source: OEKOTOP)

Climatic zone	Factors of relevance for biogas generation	As biogas zone:
Tropical rain forest	Annual rainfall > 1500 mm; temperature fairly constant at 25–28 °C; little animal husbandry due to various diseases, i.e. scarcity of dung; vegetable waste from permacultures and gardening	unfavorable
Wet savanna	Water usually available all year (rainfall: 800–1500 mm), livestock farming on the increase, integral farms (crop farming + livestock)	favorable
Dry savanna	Short rainy season, long dry season; most livestock pastured, but some integral farming	possible
Thornbush steppe	Short rainy season (rainfall: 200-400 mm) extensive-type pasturing (nomads, cattle farmers), dung uncollectable; shortage of water	unsuitable
Dry hot desert	— — —	unsuitable

prevailing climatic conditions are decisive and must be ascertained on the spot.

Soil conditions

Since the digesters of simple biogas plants are situated underground, the temperature of the soil is of decisive importanc.. It depends on the surface structure, the type of soil and the water content. The soil temperature usually varies less than the air temperature, e.g. tropical soils show nearly constant temperature at a depth of 30–60 cm. Due to lower absorption, the temperature amplitude of light soils is smaller than of dark soils. Since moist soil appears darker than dry soil, the same applies with regard to temperature amplitude. As a rule of thumb, the region's mean annual temperature may be taken as the soil temperature in tropical areas.

For biogas plants with unlined digesters and/or underground masonry, it is important to know the stability of the soil structure. The stability of a given soil increases along with the bedding density. Natural soils are generally stable enough for biogas plants. Caution is called for, however, in the case of alluvial and wet, silty soils. Most of the laterite soil prevailing in the tropics shows high structural stability and is therefore quite suitable for biogas plants with unlined digesters. Unlined earth pits usually become more or less impermeable within a short time, but preparatory seepage trials should be conducted in exploratory holes, just to make sure. Previous experience has shown that seepage can drop to below 5% of the initial rate within a week. In the case of large-scale biogas plants, it is always advisable to have an expert check the soil stability.

Biogas plants should never be located in groundwater, areas subject to flooding, or near wells. On the other hand, an adequate supply of water must be available in the immediate vicinity of the biogas plant, because the substrate must be diluted. If the direction of groundwater flow is known, the biogas plant should be placed downstream of the well.

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3.2 Suitable Types of Biomass and Their Characteristics

Practically any kind of watery organic substance is suitable for anaerobic digestion. The agricultural residues and waste materials that can be used as substrate for biogas plants consist chiefly of:

- waste from animal husbandry, e.g. dung, urine, fodder residue and manure,
- vegetable waste, e.g. straw, grass, garden residue, etc. (though such materials do not ferment well alone),
- household waste like night soil, garbage, wastewater, etc.

Solid and liquid agroindustrial waste materials, from slaughterhouses for example, and wastewater from sugar/starch processing are not gone into here, since small-scale biogas plants of simple design would not suffice in that connection (cf. chapter 6).

Waste from animal husbandry

Most simple biogas plants are "fueled" with manure (dung and urine), because such substrates usually ferment well and produce good biogas yields. Quantity and composition of manure are primarily dependent on:

- the amount of fodder eaten and its digestibility; on average, 40–80% of the organic content reappears as manure (cattle, for example, excrete approximately 1/3 of their fibrous fodder),
- quality of fodder utilization and the liveweight of the animals.

It is difficult to offer approximate excrement-yield values, because they are subject to wide variation. In the case of cattle, for example, the yield can amount to anywhere from 8 to 40 kg per head and day, depending on the strain in question and the housing intensity. Manure yields should therefore be either measured or calculated on a liveweight basis, since there is relatively good correlation between the two methods.

The quantities of manure listed in table 3.2 are only then fully available, if all of the animals are kept in stables all of the time and if the stables are designed for catching urine as well as dung (cf. chapter 3.3).

Thus, the stated values will be in need of correction in most cases. If cattle are only kept in night stables, only about 1/3 to 1/2 as much manure can be collected. For cattle stalls with litter, the total yields will include 2–3 kg litter per animal and day.

Table 3.2: Standard liveweight values of animal husbandry and average manure yields (dung and urine) as percentages of liveweight (Source: Kaltwasser 1980, Williamson and Payne 1980)

| Species | Daily manure yield as % of liveweight | | Fresh-manure solids[1] | | Liveweight (kg) |
	dung	*urine*	*TS (%)*	*VS (%)*	
Cattle	5	4–5	16	13	135–800
Buffalo	5	4–5	14	12	340–420
Pigs	2	3	16	12	30– 75
Sheep/goats[2]	3	1–1.5	30	20	30–100
Chickens	4.5		25	17	1.5– 2
Human	1	2	20	15	50– 80

[1] The TS-content of urine is approx. 5% for all species
[2] Males are up to twice as heavy as females

Table 3.3: TS and VS-contents of green plants
(Source: Memento de l'agronome 1984)

Material	TS (%)	VS (% of TS)
Rice straw	89	93
Wheat straw	82	94
Corn straw	80	91
Fresh grass	24	89
Water hyacinth	7	75
Bagasse	65	78
Vegetable residue	12	86

Vegetable waste

Crop residue and related waste such as straw, cornstalks, sugar-beet leaves, etc. are often used as fodder and sometimes processed into new products, e.g. straw mats. Consequently, only such agricultural "waste" that is not intended for some other use or for composting should be considered.

Most green plants are well-suited for anaerobic fermentation. Their gas yields are high, usually above that of manure (cf. table 3.5). Wood and woody parts of plants resist anaerobic fermentation and should therefore not be used in biogas plants. Due to the poor flow properties of plant material and its tendency to form floating scum, it can only be used alone in a batch-type plant. In practice, however, batch plants are unpopular because of the need for intermittent charging and emptying.

In continuous-type family-size biogas plants, crop residue therefore should only be used

Table 3.4: Digestion characteristics of animal-husbandry residues (Source: OEKOTOP)

Substrate	Scum formation/ sedimentation		Digestion	Recommended retention time[5] (days)	Gas yield compared to cattle manure
Cattle manure	none[1]	none	very stable	60– 80	100%
ditto, plus 10% straw	heavy	slight	very stable	60–100	120%
Pig manure	slight to heavy[2]	heavy to slight[2]	Danger of "tilting", i.e. acidification, at the beginning; slow run-up with cattle manure necessary	40– 60	200%
ditto, plus 10% straw	heavy	slight	ditto	60– 80	...
Chicken manure[3]	slight to heavy[4]	heavy	Slow run-up with cattle manure advisable; danger of "tilting"	80	200%
Sheep/goat manure manure	medium to heavy	none	stable	80–100	80%

[1] Dry manure and manure from cattle fed with fiber-rich fodder tends more toward scum formation.
[2] Heavily dependent on type of fodder used.
[3] Very little empirical data available.
[4] Pronounced scum formation, if feathers get into the digester.
[5] Practical experience shows that prolonged retention (up to 100 days) can preclude scum formation and sedimentation.

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as an addition to animal excrements. Any fibrous material like straw has to be chopped up to 2–6 cm — and even that does not fully preclude scum formation.

Digestion characteristics and gas yields

As long as the total solids content of the substrate does not substantially exceed 10%, simple biogas plants can be expected to operate smoothly on a mixture of animal excrements and plant material (straw, fodder waste).

Manure from ruminants, particularly cattle, is very useful for starting the fermentation process, because it already contains the necessary methanogenic bacteria. On the other hand, the gas yield from cattle dung is lower than that obtained from chickens or pigs, since cattle draw a higher percentage of nutrients out of the fodder, and the leftover lignin complexes from high-fiber fodder are very resistant to anaerobic fermentation. Urine, with its low organic content, con-

Table 3.5: Mean gas yields from various types of agricultural biomass (Source: OEKOTOP, compiled from various sources)

Substrate	Gas-yield range (1/kg VS[1])	Average gas yield (1/kg VS[1])
Pig manure	340–550	450
Cow manure	150–350	250
Poultry manure	310–620	460
Horse manure	200–350	250
Sheep manure	100–310	200
Stable manure	175–320	225
Grain straw	180–320	250
Corn straw	350–480	410
Rice straw	170–280	220
Grass	280–550	410
Elephant grass	330–560	445
Bagasse	140–190	160
Vegetable residue	300–400	350
Water hyacinth	300–350	325
Algae	380–550	460
Sewage sludge	310–640	450

[1] Fed volatile-solids

Table 3.6: C/N-ratios of varios substrates (Source: Barnett 1978)

Substrate	C/N
Urine	0.8
Cattle dung	10–20
Pig dung	9–13
Chicken manure	5–8
Sheep/goat dung	30
Human excrements	8
Grain straw	80–140
Corn straw	30–65
Fresh grass	12
Water hyacinth	20–30
Vegetable residue	35

tributes little to the ultimate gas yield but substantially improves the fertilizing effect of the digested slurry and serves in diluting the substrate.

The carbon(C)/nitrogen(N)-ratio of animal and human excrements is normally favorable for the purposes of anaerobic fermentation (9–25:1), while that of plant material usually indicates an excessive carbon content.

In many cases, various substrates should be mixed together in order to ensure a favorable gas yield while stabilizing the fermentation process and promoting gas production. The following formulae can be used to calculate the C/N-ratio and total-solids content of a given mixture:

$$MC/N = \frac{(C/N1 \times W1) + (C/N2 \times W2) + \ldots + (C/Nn \times Wn)}{W1 + W2 \times \ldots + Wn}$$

$$MTS = \frac{(TS1 \times W1) + (TS2 \times W2) + \ldots + (TSn \times Wn)}{W1 + W2 + \ldots + Wn}$$

MC/N = C/N-ratio of mixed substrate,
MTS = TS-content of mixed substrate,
C/N = C/N-ratio of individual substrate,
W = weight of individual substrate,
TS = TS-content of fresh material.

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3.3 Agricultural/Operational Prerequisites and Stock-farming Requirements

In order to fulfill the prerequisites for successful installation and operation of a biogas plant, the small farm in question must meet three basic requirements regarding its agricultural production system:

- availability of sufficient biomass near the biogas plant,
- use for digested slurry as fertilizer,
- practical use(s) for the biogas yield.

Farms marked by a good balance between animal husbandry and crop farming offer good prerequisites for a biogas tie-in. Unfortunately, however, such farms are rare in tropical countries. In numerous Third World countries, animal husbandry and stock farming are kept separate by tradition.

As the world population continues to grow, and arable land becomes increasingly scarce as a result, the available acreage must be used more intensively. In wet savannas, for example, the fallow periods are being shortened, even though they are important for maintaining soil fertility. In order to effectively counter extractive agriculture, animal husbandry must be integrated into the crop farming system, not least for its fertilizing effect. On the other hand, systematic manuring is only possible as long as collectible dung is allowed to accumulate via part-time or full-time stabling.

The installation of a biogas plant can be regarded as worthwhile, if at least 20–40 kg manure per day is available as substrate. This requires keeping at least 3–5 head of cattle, 8–12 pigs or 16–20 sheep/goats in a round-the-clock stabling arrangement. The achievable gas yield suffices as cooking fuel for a family of 4–6 persons. That, in turn, means that the farm must be at least about 3 hectares in size, unless either freely accessible pastures are available or extra fodder is procured. Crop residue like rice straw, sorghum straw, cornstalks, banana stalks, etc. should be chopped up, partially com-

Fig. 3.2: Integration of a biogas plant into the agricultural production cycle (Source: OEKOTOP)
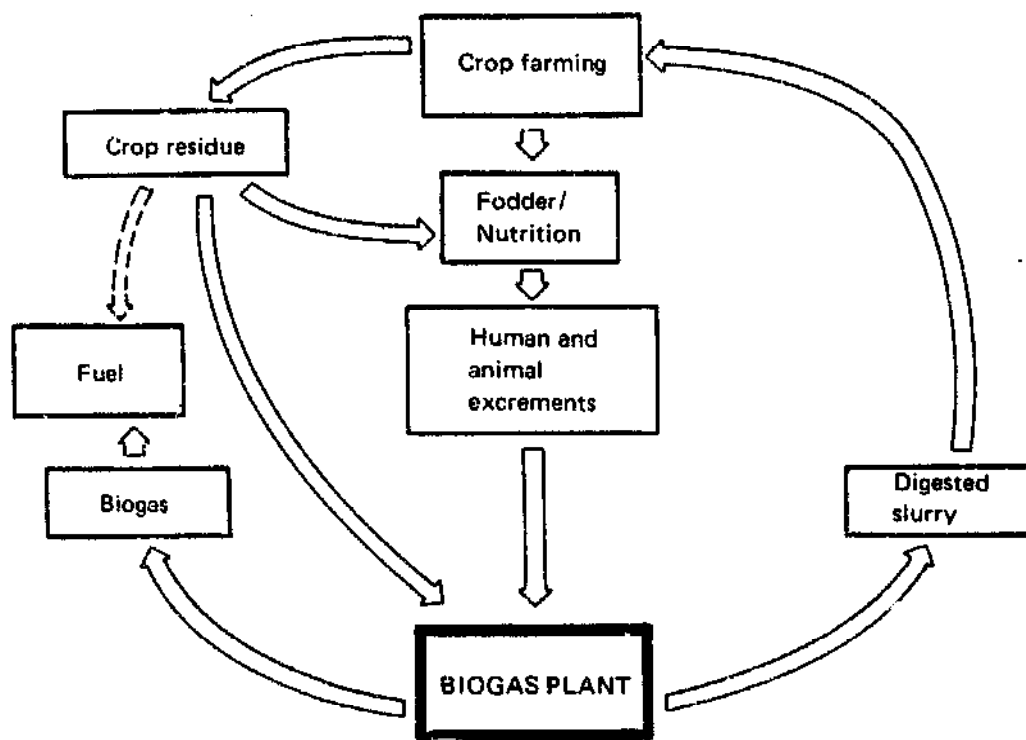

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Table 3.7: Biogas compatibility of farm types (Source: OEKOTOP)

Type of farm	Characteristics of relevance to biogas generation	Rating as site for biogas plant
Stock farming only	Pasturing (nomadic, ranching, etc.)	unsuitable
	Intensive stationary fattening	suitable
Crop farming only	Crop residue only; fermentation difficult	normally unsuitable ·
Mixed Agriculture		
Stock farming for:		
− animal power	Mostly nighttime stabling; only a few animals; 50% of dung collectible	possible
− meat production		
extensive	Pasturing; no stabling; dung wasted	unsuitable
intensive	Fattening in stables; dung directly usable	suitable
− milk production	Frequently permanent stabling; all dung and urine usable	suitable
Crop farming:		
− vegetables	Near house; crop residue and water available year-round	possible[1]
− field-tilling		
unirrigated	1 harvest per year, scarcity of fodder, long-distance hauling of water and manure	unsuitable
irrigated	2−3 harvests per year; water availabl ·, small fields	possible[1]

[1] If vegetable waste is digested together with animal excrements.

posted and mixed with animal excrements for use in the fermentation process (cf. chapter 3.2).

Adding a biogas plant to an integrated agricultural production system not only helps save firewood and preserve forests, but also contributes toward sustained soil fertility through organic fertilization and ensures the long-term crop-bearing capacity of the soil. Work involving the dissemination of biogas technologies must account for and call attention to that complex relationship. If no organic fertilizing has been done before, a biogas plant will mean more work. Organic waste has to be collected and afterwards spread on the fields. Only if the owner is willing to invest the extra effort can the biogas plant be expected to serve well in the long term.

There are two central demands to be placed on the stock-farming system in relation to biogas utilization:

− permanent or part-time stabling or penning and
− proximity of the stables or pens to the place of gas utilization (usually the farmhouse).

If the distance between the stables/pens and the place of gas utilization is considerable, either the substrate must be hauled to the biogas plant (extra work) or the gas must be transferred to the place of use (cost of installing a supply pipe). Either of the two would probably doom the biogas plant to failure. The best set of circumstances is given, when
− the animal excrements can flow directly into the biogas plant by exploiting a natural gradient,

— the distance of flow is short, and
— the stables have a concrete floor to keep contamination like soil and sand from getting into the plant while allowing collection of urine.

Cattle pens

Dung from earth-floor pens has a very high total-solids content (TS up to 60%), and the urine is lost. Daily collection is tedious and there is no way to prevent sand from getting into the digester. Consequently, at the same time a biogas plant is being installed, concrete floors should be installed in such pens and provided with a collecting channel. This increases the total cost of the biogas plant, but is usually justified, since it lowers the subsequent work input, helps ensure regular feeding of the plant, reduces the chance of hoof disease and keeps sand and stones out of the digester. The overall effect is to en-hance acceptance of the biogas plant.

The collecting channels can be designed as open gutters or covered ducts. Concrete split tiles serve well as construction material for the second (more expensive) version. The slots should be about 2–3 cm wide, i.e. wide enough to let the dung pass through, but not wide enough to cause injury to the animals.

Cattle dung dries rapidly in a hot climate, particularly if the pen has no roof. The cleaning water also serves to liquefy the dung and reduce its TS content to 5–10% for the purposes of fermentation. The main advantage of this system is that the pens can be cleaned and the biogas plant filled in a single operation. The collecting channel should be designed to yield a floating-manure system with gates at the ends, so that a whole day's dung and cleaning water can collect at once. The advantages:

— easy visual control of the daily sub-strate input,
— prevention of collecting-channel blockage due to dung sticking to the walls and drying out,
— adding the substrate at the warmest time of day, which can be very important in areas with low nighttime temperatures.

Fig. 3.3: Pen with concrete floor and collecting channel for dung and urine.
1 Water trough, 2 Feeding trough, 3 Collecting channel, 4 Sand and rocks,
5 Concrete (Source: OEKOTOP)
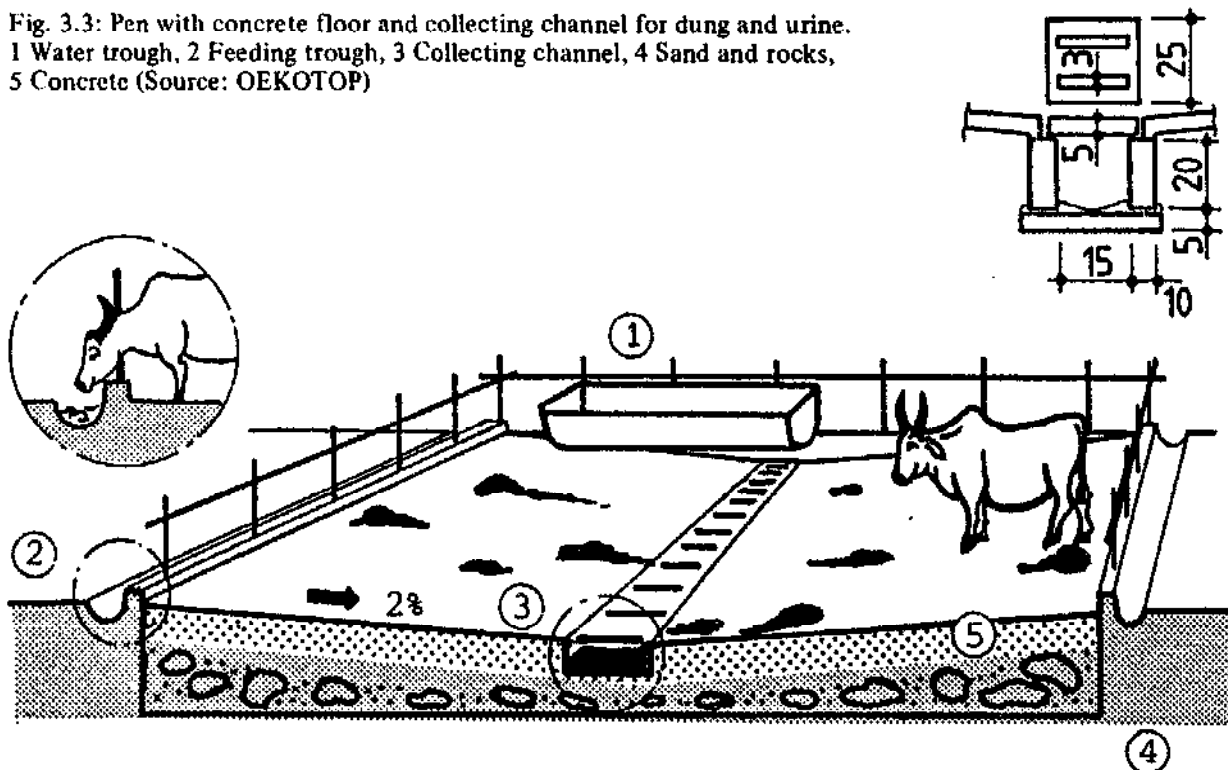
Intensive forms of animal husbandry often involve the problem of excessive water consumption for cleaning, which leads to large quantities of wastewater, dilute substrate and unnecessarily large biogas plants (cf. chapter 6). In areas where water is scarce, the digester drain-water can be used for scrubbing down the pens and diluting the fresh substrate, thus reducing the water requirement by 30—40%.

Stables

Differentiation is generally made between:
— stabling systems with litter and
— stabling systems without litter,
with the design details of the stalls appropriate to the type of animal kept.
For use in a biogas plant, any straw used as litter must be reduced in size to 2—6 cm. Sawdust has poor fermenting properties and should therefore not be used.

Cattle shelter

Variants suitable for connection to a biogas plant include:
— Stanchion barns with a slurry-flush or floating removal system (no litter) or dung collecting (with litter),
— Cow-cubicle barns with collecting channel (no litter).

Piggeries

The following options are well-suited for combination with a biogas plant:
— barns with fully or partially slotted floors (no litter),
— lying bays with manure gutter (no litter),
— group bays (with or without litter).
Liquid manure from swine normally has better flow properties than liquid manure from cattle, the main reason being that swine eat less fibrous material. Additionally, though, swine drop more urine than dung.
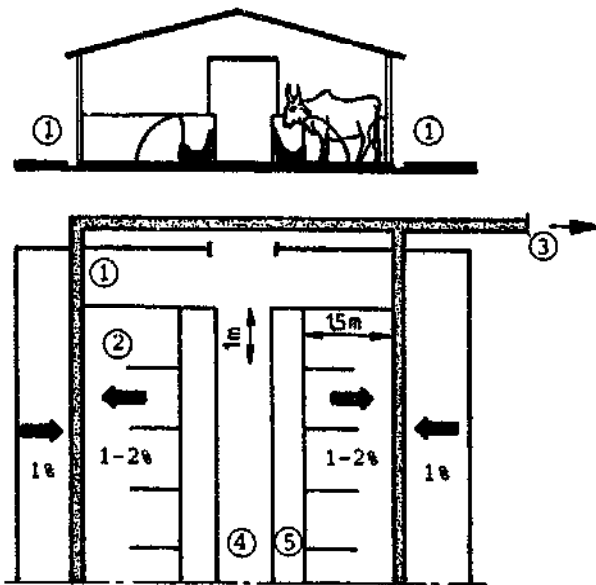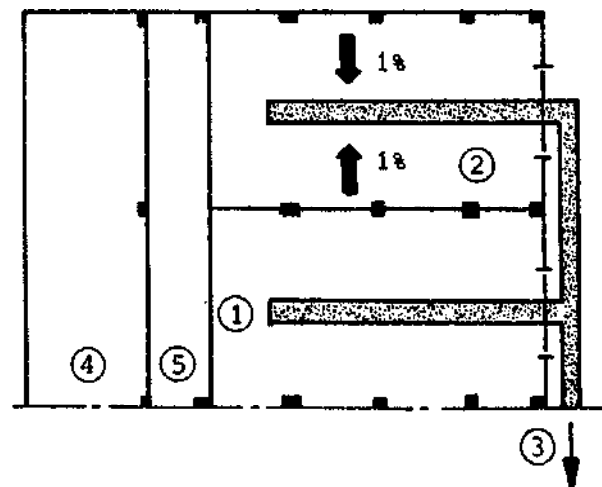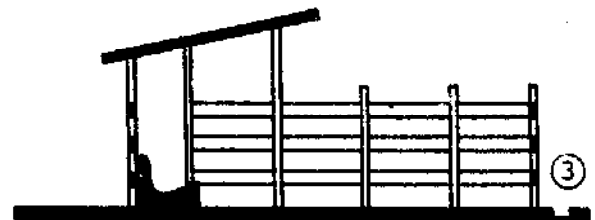

Fig. 3.4: Stanchion barn with floating gutter. 1 Collecting channel, 2 Stable, 3 Floating gutter leading to the biogas plant, 4 Feeding aisle, 5 Feeding trough (Source: OEKOTOP)

Fig. 3.5: Cow-cubicle barn with floating gutter. 1 Collecting channel, 2 Cubicle, 3 Floating gutter leading to the biogas plant, 4 Feeding aisle, 5 Feeding trough (Source: OEKOTOP)
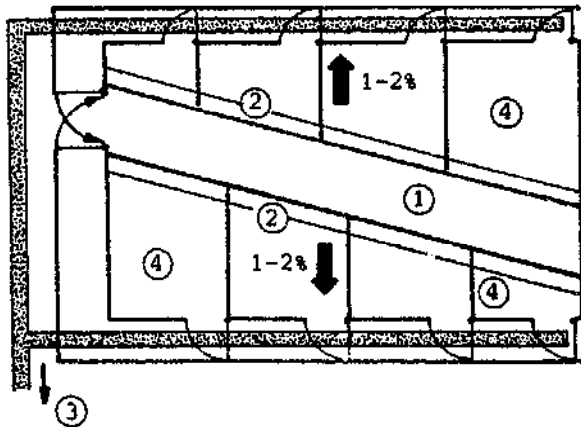

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Fig. 3.6: Piggery with group bays (no litter).
1 Feeding aisle, 2 Feeding trough, 3 Floating gutter
leading to the biogas plant, 4 Bay (pigpen) (Source:
Manuel et Preas D'Elevage No. 3, 1977)

In tropical countries, few pigsties have fully or partially slotted floors. Most pigs are kept in group bays. Figure 3.6 shows a schematic representation of a piggery with bays of different size to accommodate animals of various weight categories. The animals are moved in groups from one bay to the next as they grow.

Chicken coops

Hens kept in battery-brooding cages never have litter. Despite the name, straw yards can be managed with or without litter.
In either system, the dry droppings are collected, transferred to the biogas plant and diluted to make them flowable. Feathers and sand are always problematic, since they successfully resist removal from the substrate. In many cases, the coop is only cleaned and disinfected once after the entire population is slaughtered. As a rule such systems are not suitable as a source of substrate for biogas plants.

Photo 3: Feeding the plant and mixing the substrate (Source: OEKOTOP, BEP Burundi)

Photo 4: Fertilizing with digested slurry (Source: BEP Caribbean)

Photo 5: Cattle shelter feeding into a biogas plant (foreground) (Source: BEP Burkina Faso)

3.4 Fertilizing with Digested Slurry

The practice of regular organic fertilizing is still extensively unknown in most tropical and subtropical countries. Due, however, to steady intensification of agricultural methods, e.g. abbreviated fallow intervals, some form of purposeful organic fertilizing, naturally including the use of digested slurry as fertilizer, would be particularly useful as a means of maintaining tropical soil fertility. Since Third World farmers have little knowledge of or experience in organic fertilizing methods, particularly with regard to the use of digested slurry, the scope of the following discussion is limited to the general plant-growth efficiency factors of digested slurry.

Fermentation-induced modification of substrate

— Anaerobic digestion draws carbon, hydrogen and oxygen out of the substrate. The essential plant nutrients (N, P, K) remain, at least in principle, in place. The composition of fertilizing agents in digested slurry depends on the source material and therefore can be manipulated within certain limits.

— For all practical purposes, the volume of the source material remains unchanged, since only some 35—50% of the organic substances (corresponding to 5—10% of the total volume) is converted to gas.

— Fermentation reduces the C/N-ratio by removing some of the carbon, which has the advantage of increasing the fertilizing effect. Another favorable effect is that organically fixed nitrogen and other plant nutrients become mineralized and, hence, more readily available to the plants.

— Well-digested slurry is practically oderless and does not attract flies.

— Anaerobic digestion kills off or at least deactivates pathogens and worm ova, though the effect cannot necessarily be referred to as hygienization (cf. Table 3.8). Ninety-five

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Table 3.8: Survival time of pathogens in biogas plants (Source: Anaerobic Digestion 1985)

Bacteria	Thermophilic fermentation 53–55 °C		Mesophilic fermentation 35–37 °C		Psycrophilic fermentation 8–25 °C	
	Fatality Days	Rate (%)	Fatality Days	Rate (%)	Fatality Days	Rate (%)
Salmonella	1–2	100.0	7	100.0	44	100.0
Shigella	1	100.0	5	100.0	30	100.0
Poliviruses			9	100.0		
Schistosoma ova	hours	100.0	7	100.0	7–22	100.0
Hookworm ova	1	100.0	10	100.0	30	90.0
Ascaris ova	2	100.0	36	98.8	100	53.0
Colititre	2	$10^{-1}-10^{-2}$	21	10^{-4}	40–60	$10^{-5}-10^{-4}$

percent of the ova and pathogens accumulate in the scum and sediment. Plant seeds normally remain more or less unaffected.

-- Compared to the source material, digested slurry has a finer, more homogeneous structure, which makes it easier to spread.

Fertilizing properties

The fertilizing properties of digested slurry are determined by how much mineral substances and trace elements it contains; in tropical soil, the nitrogen content is not necessarily of prime importance -- lateritic soils, for example, are more likely to suffer from a lack of phosphorus. The organic content of digested slurry improves the soil's texture, stabilizes its humic content, intensifies its rate of nutrient-depot formation

and increases its water-holding capacity. It should be noted that a good water balance is very important in organically fertilized soil, i.e. a shortage of water can wipe out the fertilizing effect.

Very few data on yields and doses are presently available with regard to fertilizing with digested slurry, mainly because sound scientific knowledge and information on practical experience are lacking in this very broad domain. Table 3.10 lists some yield data on digested-slurry fertilizing in the People's Republic of China.

For a practician faced with the task of putting digested slurry to good use, the following tendential observations may be helpful:

− While the nitrogen content of digested slurry is made more readily available to the

Table 3.9: Concentration of nutrients in the digested slurry of various substrates[1] (Source: OEKOTOP, compiled from various sources)

Type of substrate	N	P_2O_5	K_2O	CaO	MgO
			– % TS –		
Cattle dung	2.3–4.7	0.9–2.1	4.2–7.6	1.0–4.2	0.6–1.1
Pig dung	4.1–8.4	2.6–6.9	1.6–5.1	2.5–5.7	0.8–1.1
Chicken manure	4.3–9.5	2.8–8.1	2.1–5.3	7.3–13.2	1.1–1.6

[1] without litter

Table 3.10: Effects of digested slurry on crop yields (Source: Chengdu 1980)

Plants tested	Quantity of digested slurry (m³/ha)	Yield with digested slurry	with liquid manure (kg/ha)	Increase (kg/ha)	(%)
Sweet potatoes	17	24000	21500	2500	12
Rice	15	6500	6000	500	8
Corn (maize)	22.5	5000	4600	400	9
Cotton	22.5	1300	1200	100	8

plants through the mineralization process, the yield effect of digested slurry differs only slightly from that of fresh substrate (liquid manure). This is chiefly attributable to nitrogen losses occurring at the time of distribution.

− Digested slurry is most effective when it is spread on the fields just prior to the beginning of the vegetation period. Additional doses can be given periodically during the growth phase, with the amounts and timing depending on the crop in question. For reasons of hygiene, however, lettuce and vegetables should not be top-dressed.

− The recommended quantities of application are roughly equal for digested slurry and stored liquid manure.

− The requisite amount of digested-slurry fertilizer per unit area can be determined as a mineral equivalent, e.g. N-equivalent fertilization. The N, P and K doses depend on specific crop requirements as listed in the appropriate regional fertilizing tables.

With a view to improving the overall effect of slurry fertilizer under the prevailing local boundary conditions, the implementation of a biogas project should include demonstration trials aimed at developing a regionally appropriate mode of digested-slurry application. For information on experimental systems, please refer to chapter 10.6 — Selected Literature.

Proceeding on the assumption that the soil should receive as much fertilizer as needed to replace the nutrients that were extracted at harvesting time, each hectare will require an average dose of about 33 kg N, 11 kg P_2O_5 and 48 kg K_2O to compensate for an annual yield of 1−1.2 tons of, say, sorghum or peanuts. Depending on the nutritive content of the digested slurry, 3−6 t of solid substance per hectare will be required to cover the deficit. For slurry with a moisture content of 90%, the required quantity comes to 30−60 t per hectare and year. That roughly corresponds to the annual capacity of a 6−8 m³ biogas plant.

Like all other forms of organic fertilizing, digested slurry increases the humic content of the soil, and that is especially important in low-humus tropical soils. Humus improves the soil's physical properties, e.g. its aeration, water retention capacity, permeability, cation-exchange capacity, etc. Moreover, digested slurry is a source of energy and nutrients for soil-inhabiting microorganisms, which in turn make essential nutrients more available to the plants. Organic fertilizers are indispensable for maintaining soil fertility, most particularly in tropical areas.

The importance of digested slurry as a fertilizer is underlined by the answers to the following questions:

− How much chemical fertilizer can be saved with no drop in yield?

− Which yield levels can be achieved by fertilizing with digested slurry, as compared

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to the same amount of undigested material, e.g. stored or fermented liquid manure?

– By how much can yields be increased over those from previously unfertilized soil? Depending on those answers, a certain monetary value can be attached to digested slurry, whereas the labor involved in preparing and applying the fertilizer must be given due consideration.

Storing and application of digested slurry

With a view to retaining the fertilizing quality of digested slurry, it should be stored only briefly in liquid form in a closed pit or tank and then applied to the fields. Liquid storage involves a certain loss of nitrogen due to the evaporation of ammonia. For that reason, and in order to limit the size of

Fig. 3.7: Slurry storage and composting. 1 Biogas plant, 2 Slurry composting pit with green cover, 3 Masonry storage pit (V = 10 Sd), 31 Sturdy wooden cover, 32 Overflow (Source: OEKOTOP)
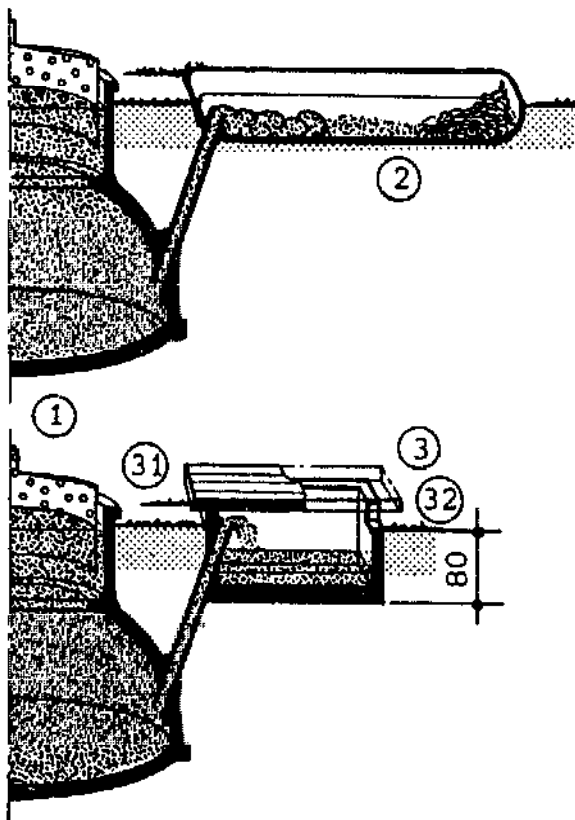
the required storage vessels (a 30-day supply corresponds to about 50% of the biogas plant volume), the storage period should be limited to 2–4 weeks. The resultant quasi-continuous mode of field fertilization (each 2–4 weeks), however, is in opposition to the standing criteria of optimum application, according to which fertilizer should only be applied 2–4 times per year, and then only during the plants' growth phase, when they are able to best exploit the additional nutrient supply.

The practice of spreading liquid digested slurry also presents problems in that not only storage tanks are needed, but transport vessels as well, and the amount of work involved depends in part on how far the digested slurry has to be transported. For example, transporting 1 ton of dung a distance of 500 m in an oxcart takes about 5 hours (200 kg per trip). Distributing the dung over the fields requires another 3 hours or so.

If, for reasons of economy and efficiency, liquid fertilizing should appear impractical, the digested slurry can be mixed with green material and composted. This would involve nitrogen losses amounting to 30–70%. On the other hand, the finished compost would be soil-moist, compact (spade able) and much easier to transport.

If irrigated fields are located nearby, the digested slurry could be introduced into the irrigating system so that it is distributed periodically along with the irrigating water.

3.5 Integral Agriculture

Integral agriculture, also referred to as biological or ecological farming, aims to achieve effective, low-cost production within a system of integrated cycles. Here, biogas technology can provide the link between animal husbandry and crop farming.
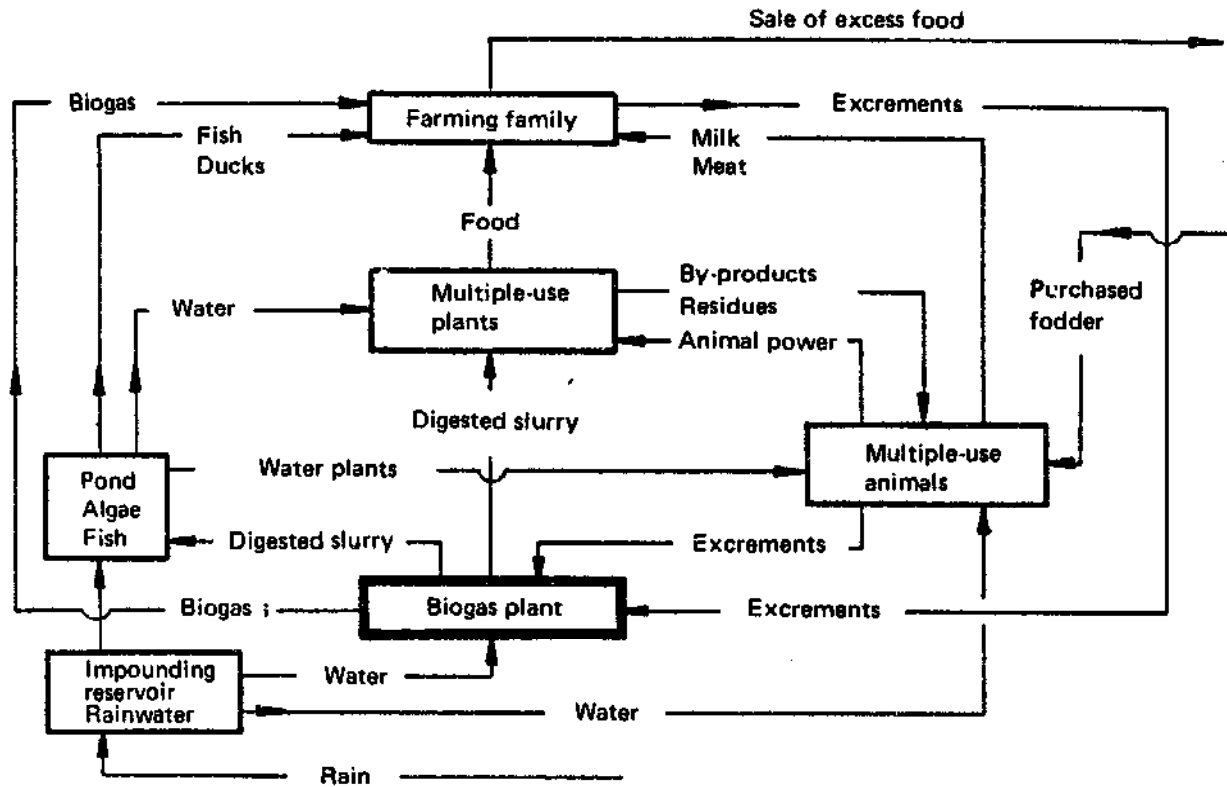
Fig. 3.8: Flow diagram for integral farming with a biogas plant
(Source: GTZ 1985)

Consider, for example, the planning of a GTZ project in Côte d'Ivoire. The project included the development of a model farm intended to exploit as efficiently as possible the natural resources soil, water, solar energy and airborne nitrogen.

The integral agricultural system "Eco-ferme" (ecofarm) comprises the production elements gardening, crop farming (for food and animal fodder), stock farming (for meat and milk) and a fishpond. A central component of such closed-loop agricultural production is the biogas plant, which produces both household energy and digested slurry for use in the fishpond and as a fertilizer.
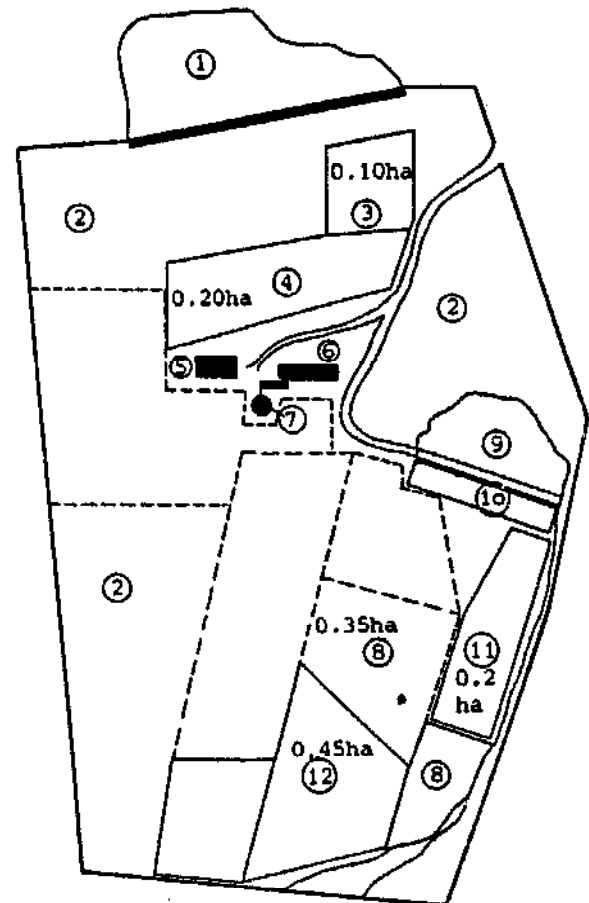
Fig. 3.9: Site plan of the Bouaké Ecofarm in Côte d'Ivoire. 1 Impounding reservoir for rainwater, 2 Fallow land, 3 Manioc (1st year), 4 Yams and Manioc (2nd year), 5 Farmhouse, 6 Stables, 7 Biogas plant, 8 Sugar cane, 9 Water reservoir, 10 Fishpond, 11 Vegetable garden, 12 Various food plants (Source: GTZ 1985)

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The average family-size "eco-ferme" has 3 ha of farmland with the following crops:

Fodder plants

Panicum (for the rainy season)	0.15 ha
Sugar cane (for the dry season)	0.50 ha
Leucaena and brachiaria (mixed culture	0.50 ha
Panicum, brachiaria and centrosema (mixed culture)	0.50 ha

Food plants

Manioc	0.20 ha
Corn	0.40 ha
Yams	0.10 ha
Potatoes — beans	0.10 ha
Vegetables	0.20 ha
Rice and miscellaneous crops	0.17 ha

Four milk cows and three calves are kept year-round in stables. The cattle dung flows via collecting channels directly into a 13 m³ biogas plant. The biogas plant produces 3.5—4 m³ biogas daily for cooking and lighting. Part of the digested slurry is allowed to flow down the natural gradient into an 800 m² fishpond in order to promote the growth of algae, which serves as fish food. The remaining digested slurry is used as crop fertilizer.

4. Balancing the Energy Demand with the Biogas Production

All extension-service advice concerning agricultural biogas plants must begin with an estimation of the quantitative and qualitative energy requirements of the interested party. Then, the biogas-generating potential must be calculated on the basis of the given biomass incidence and compared to the energy demand. Both the energy demand and the gas-generating potential, however, are variables that cannot be very accurately determined in the planning phase.

In the case of a family-size biogas plant intended primarily as a source of energy, implementation should only be recommended, if the plant can be expected to cover the calculated energy demand.

Since determination of the biogas production volume depends in part on the size of the biogas plant, that aspect is included in this chapter.

4.1 Determining the Energy Demand

The energy demand of any given farm is equal to the sum of all present and future consumption situations, i.e. cooking, lighting,

Fig. 4.1: Balancing the energy demand with the biogas production (Source: OEKOTOP)
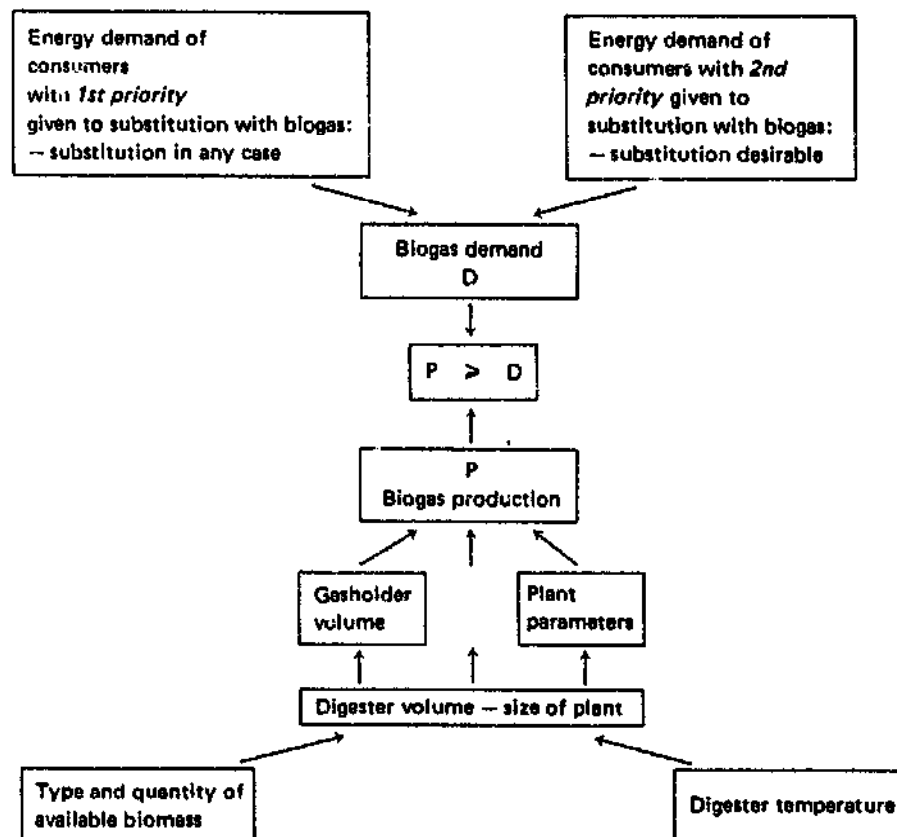
cooling, power generation, etc. With deference to the general orientation of this manual, emphasis is placed on determining the energy demand of a typical family farm.

Experience shows that parallel calculations according to different methods can be useful in avoiding errors in calculating the gas/ energy demand.

Table 4.1: Outline for determining biogas demand (Source: OEKOTOP)

Energy consumers	data	Biogas demand (l/d)
1. *Gas for cooking* (Chapter 5.5.3)		
Number of persons	. . . .	
Number of meals	. . . .	
Present energy consumption	. . . .	
Present source of energy	. . . .	
Gas demand per person and meal (Table 5.17)	. . . .	
Gas demand per meal	. . . .	
Anticipated gas demand		. . . .
Specific consumption rate of burner	. . . .	
Number of burners	. . . .	
Duration of burner operation	. . . .	
Anticipated gas demand		. . . .
Total anticipated cooking-gas demand		. . . .
2. *Lighting* (Chapter 5.5.3)		
Specific gas consumption per lamp (Table 5.20)	. . . .	
Number of lamps	. . . .	
Duration of lamp operation	. . . .	
Gas demand		. . . .
3. *Cooling* (Chapter 5.5.3)		
Specific gas consumption × 24 h (Table 5.22)	. . . .	. . . .
4. *Engines* (Chapter 5.5.4)		
Specific gas consumption per kWh	. . . .	
Engine output	. . . .	
Operating time	. . . .	
Gas demand		. . . .
5. *Miscellaneous* consumers		
Gas demand	. . . .	. . . .
Anticipated increase in consumption (%)		. . . .
Total biogas demand		. . . .
1st-priority consumers		. . . .
2nd-priority consumers		. . . .
3rd-priority consumers		. . . .

The following alternative modes of calculation are useful:

Determining biogas demand on the basis of present consumption
. . ., e.g. for ascertaining the cooking-energy demand. This involves either measuring or inquiring as to the present rate of energy consumption in the form of wood/charcoal, kerosene and/or bottled gas.

Calculating biogas demand via comparable-use data
Such data may consist of:
— empirical values from neighboring systems, e.g. biogas consumption per person and meal,
— reference data taken from pertinent literature (cf. chapter 5.5), although this approach involves considerable uncertainty, since cooking-energy consumption depends on local culture-dependent cooking and eating habits and can therefore differ substantially from case to case.

Estimating biogas demand by way of appliance consumption data and assumed periods of use
This approach can only work to the extent that the appliances to be used are known in advance, e.g. a biogas lamp with a specific gas consumption of 120 l/h and a planned operating period of 3 h/d, resulting in a gas demand of 360 l/d.

Then, the interested party's energy demand should be tabulated in the form of a requirements list (cf. table 4.1). In that connection, it is very important to attach relative priority values to the various consumers, e.g.:
1st priority: applies only when the biogas plant will cover the demand.
2nd priority: coverage is desirable, since it would promote plant usage.
3rd priority: excess biogas can be put to these uses.

4.2 Determining the Biogas Production

The quantity, quality and type of biomass available for use in the biogas plant constitutes the basic factor of biogas generation. The biogas incidence can and should also be calculated according to different methods applied in parallel.

Measuring the biomass incidence (quantities of excrement and green substrate)

This is a time-consuming, somewhat tedious approach, but it is also a necessary means of adapting values from pertinent literature to unknown regions. The method is rather inaccurate if no total-solids measuring is included. Direct measurement can, however, provide indication of seasonal or fodder-related variance if sufficiently long series of measurements are conducted.

Determining the biomass supply via pertinent-literature data
(cf. tables 3.2/3.3)

According to this method, the biomass incidence can be determined at once on the basis of the livestock inventory. Data concerning how much manure is produced by different species and per liveweight of the livestock unit are considered preferable.
Dung yield = liveweight (kg) × no. of animals × specific quantity of excrements (in % of liveweight per day, in the form of moist mass, TS or VS).

Determining the biomass incidence via regional reference data

This approach leads to relatively accurate information, as long as other biogas plants are already in operation within the area in question.

Table 4.2: Outline for determining biomass incidence (Source: OEKOTOP)

Source of biomass	Moist weight (kg/d)	TS/VS weight (kg/d)
Animal dung		
Number of cattle:		
Dung yield per head	. . . .	. . . .
Amount collected		
Dung yield from cattle	. . . .	. . . .
Number of pigs:		
Dung yield per pig	. . . .	. . . .
Amount collected:		
Dung yield from pigs	. . . .	. . . .
Sheep, camels, horses etc.	. . . .	. . . .
Green matter		
1. grass, etc.	. . . .	. . . .
2.	. . . .	. . . .
Night soil		
Number of persons:		
Dung yield from night soil	. . . .	. . . .
Total biomass incidence	. . . .	. . . .
Category 1	. . . .	. . . .
Category 2	. . . .	. . . .

Determining biomass incidence via user survey

This approach is necessary if green matter is to be included as substrate.

It should be kept in mind that the various methods of calculation can yield quite disparate results that not only require averaging by the planner, but which are also subject to seasonal variation.

The biomass supply should be divided into two categories:

Category 1: quick and easy to procure,
Category 2: procurement difficult, involving a substantial amount of extra work.

4.3 Sizing the Plant

The size of the biogas plant depends on the quantity, quality and kind of available biomass and on the digesting temperature.

Sizing the digester

The size of the digester, i.e. the digester volume (Vd), is determined on the basis of the chosen retention time (RT) and the daily substrate input quantity (Sd).

$$Vd = Sd \times RT \ (m^3 = m^3/day \times number \ of \ days)$$

The retention time, in turn, is determined by the chosen/given digesting temperature (cf. fig. 5.2).

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For an unheated biogas plant, the temperature prevailing in the digester can be assumed as 1–2 K above the soil temperature. Seasonal variation must be given due consideration, however, i.e. the digester must be sized for the least favorable season of the year. For a plant of simple design, the retention time should amount to at least 40 days. Practical experience shows that retention times of 60–80 days, or even 100 days or more, are no rarity when there is a shortage of substrate. On the other hand, extra-long retention times can increase the gas yield by as much as 40%.

The substrate input depends on how much water has to be added to the substrate in order to arrive at a solids content of 4–8%.

Substrate input (Sd) = biomass (B) + water (W) (m³/d)

In most agricultural biogas plants, the mixing ratio for dung (cattle and/or pigs) and water (B : W) amounts to between 1 : 3 and 2 : 1 (cf. table 5.7).

Calculating the daily gas production (G)

The amount of biogas generated each day (G, m³ gas/d), is calculated on the basis of the specific gas yield (Gy) of the substrate and the daily substrate input (Sd).
The calculation can be based on:

a) The volatile-solids content

G = kg VS-input × spec. Gy (solids)

b) the weight of the moist mass

G = kg biomass × spec. Gy (moist mass)

c) standard gas-yield values per livestock unit (LSU)

G = no. of LSU × spec. Gy (species)

Table 4.3 lists simplified gas-yield values for cattle and pigs. A more accurate estimate can be arrived at by combining the gas-yield values from, say, table 3.5 with the correction factors for digester temperature and retention time shown in figure 5.2.

$$Gy_{T,RT} = mGy \times f_{T,RT}$$

$Gy_{T,RT}$ = gas yield as a function of digester temperature and retention time

mGy = average specific gas yield, e.g. 1/kg VS (table 3.5)

$f_{T,RT}$ = multiplier for the gas yield as a function of digester temperature and retention time (cf. fig. 5.2)

As a rule, it is advisable to calculate according to several different methods, since the available basic data are usually very imprecise, so that a higher degree of sizing certainty can be achieved by comparing and averaging the results.

Establishing the plant parameters

The degree of safe-sizing certainty can be increased by defining a number of plant parameters:

Specific gas production (Gp)
i.e. the daily gas-generation rate per m³ digester volume (Vd), is calculated according to the following equation:

$$Gp = G : Vd \ (m^3 \ gas/m^3 \ Vd \times d)$$

Digester loading (Ld)

$$Ld = TS \ (VS) \ input/m^3 \ digester \ volume$$
$$(kg \ TS \ (VS)/m^3 \ Vd \times d)$$

Then, a calculated parameter should be checked against data from comparable plants in the region or from pertinent literature.

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Table 4.3: Simplified gas-yield values for substrate from cattle and pigs (digesting temperature: 22–27 °C) (Source: OEKOTOP)

Type of housing/ manure	Cattle, live wt. 200–300 kg manure yield (kg/d)	Gas yield (l/d) RT=60	Gas yield (l/d) RT=80	Buffalo, live wt. 300–450 kg manure yield (kg/d)	Gas yield (l/d) RT=60	Gas yield (l/d) RT=80	Pigs, live wt 50–60 kg manure yield (kg/d)	Gas yield (l/d) RT=40	Gas yield (l/d) RT=60
24-h stabling									
– dung only (moist), unpaved floor (10% losses)	9–13	300–450	350–500	14–18	450–540	300–620	–	–	–
– dung and urine, concrete floor	20–30	350–510	450–610	30–40	450–600	540–710	2.5–3.0	120–140	150–180
– stable manure (dung + 2 kg litter), concrete floor	22–32	450–630	530–730	32–42	550–740	630–890	–	–	–
Overnight stabling									
– dung only (10% losses)	5– 8	180–270	220–310	8–10	240–300	290–360	–	–	–
– dung and urine, concrete floor	11–16	220–320	260–380	16–20	260–330	330–410	–	–	–
1 kg/d moist dung		~35	~40		~34	~40		–	–
1 l/d manure		~20	~25		~20	~24		~50	~60
1 kg/d manure		~22	~27		~22	~26		–	–
1 kg TS/d		~200	~240		~200	~240		~270	~340
1 kg VS/d		~250	~300		~250	~300		~350	~430

Sizing the gasholder

The size of the gasholder, i.e. the gasholder volume (Vg), depends on the relative rates of gas generation and gas consumption. The gasholder must be designed to:
- cover the peak consumption rate (Vg 1) and
- hold the gas produced during the longest zero-consumption period (Vg 2).

$$Vg1 = gc, max \times tc, max = vc, max$$
$$Vg2 = G \times tz, max$$

gc, max = maximum hourly gas consumption (m^3/h)

tc, max = time of maximum consumption (h)

vc, max = maximum gas consumption (m^3)

G = gas production (m^3/h)

tz, max = maximum zero-consumption time (h)

The larger Vg-value (Vg1 or Vg2) determines the size of the gasholder. A safety margin of 10–20% should be added. Practical experience shows that 40–60% of the daily gas production normally has to be stored.

Digester volume vs. gasholder volume (Vd : Vg)

The ratio

Vd : Vg

is a major factor with regard to the basic design of the biogas plant. For a typical agricultural biogas plant, the Vd/Vg-ratio amounts to somewhere between 3 : 1 and 10 : 1, with 5 : 1 – 6 : 1 occurring most frequently.

4.4 Balancing the Gas Production and Gas Demand by Iteration

As described in subsection 4.1, the biogas/ energy production (P) must be greater than the energy demand (D).

P ≥ D

This central requirement of biogas utilization frequently leads to problems, because small farms with only a few head of livestock usually suffer from a shortage of biomass. In case of a negative balance, the planner must check both sides – production and demand – against the following criteria:

Energy demand (D)

Investigate the following possibilities:
- shorter use of gas-fueled appliances, e.g. burning time of lamps,
- omitting certain appliances, e.g. radiant heater, second lamp,
- reduction to a partial-supply level that would probably make operation of the biogas plant more worthwhile.

The aim of such considerations is to reduce the energy demand, but only to such an extent that it does not diminish the degree of motivation for using biogas technology.

Energy supply – biogas production (P)

Examine/calculate the following options/ factors:
- the extent to which the useful biomass volume can be increased (better collecting methods, use of dung from other livestock inventories, including more agricultural waste, night soil, etc.), though any form of biomass that would unduly increase the necessary labor input should be avoided;
- the extent to which prolonged retention times, i.e. a larger digester volume, would increase the gas yield, e.g. the gas yield from cattle manure can be increased from roughly 200 l/kg VS for an RT of 40 days to as much as 320 l/kg VS for an RT of 80–100 days;
- the extent to which the digesting temperature could be increased by modifying the structure.

The aim of such measures is to determine the maximum biogas-production level that can be achieved for a reasonable amount of work and an acceptable cost of investment.

If the gas production is still smaller than the gas demand (P < D), no biogas plant should be installed.

If, however, the above measures succeed in fairly well matching up the production to the demand, the plant must be resized according to subsection 4.3.

4.5 Sample Calculations

Energy demand (D)

Basic data
8-person family, 2 meals per day.
Present rate of energy consumption: 1.8 l kerosene per day for cooking and fueling 1 lamp (0.6 l kerosene = 1 m^3 biogas).

Desired degree of coverage with biogas

Cooking: all
Lighting: 2 lamps, 3 hours each
Cooling: 60 l refrigerator

Daily gas demand (D)

Cooking
1. Present fuel demand for cooking:
1.2 l kerosene = 2 m^3 gas
2. Gas demand per person and meal:
0.15 m^3 biogas
Gas demand per meal: 1.2 m^3 biogas
Cooking-energy demand: 2.4 m^3 biogas
3. Consumption rate of gas burner:
175 l/h per flame (2-flame cooker)
Operating time: 2 x 3 h + 1 h for tea
Biogas demand: 7 h x 350 l = 2.5 m^3

Defined cooking-energy demand:
2.5 m^3 biogas/d

Lighting
Gas consumption of lamp: 120 l/h
Operating time: 2 x 3 h = 6 h
Biogas demand: 0.7 m^3/day

Cooling (60 l refrigerator)
Specific gas demand: 30 l/h
Biogas demand: 0.7 m^3/day

Total biogas demand: 3.9 m^3/d

1st priority: cooking	2.5 m^3
2nd priority: 1 lamp	0.35 m^3
3rd priority: 1 lamp/refrigerator	1.05 m^3

Biomass supply/Biogas production (P)

Basic data
9 head of cattle, 230 kg each, 24-h stabling, green matter from garden as supplement.

Daily biomass incidence

Animal dung, calculated as % liveweight (as per 1.) or as daily yield per head (as per 2.) as listed in pertinent literature.

1. Dung as % liveweight
Daily yield per head of cattle: 10% of 230 kg = 23 kg/d
Volatile solids/d: 1.8 kg VS per day and animal
Total yield: 207 kg/d (16 kg VS/d)

2. Manure yield on per-head basis
Dung yield per head of cattle: 15 kg/d
Urine: 9 l/d
Volatile solids: 9% = 2.1 kg VS/d
Total yield: 216 kg/d (19 kg VS/d)

Useful percentage: 75%
The lowest values are used as the basis of calculation.

Green matter:
20 kg agricultural waste with 30% VS.

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Total biomass incidence 170 kg/d (18 kg VS/d)   Anticipated daily biogas yield = 3.0 m³/d

Category 1: cattle   150 kg (12 kg)
Category 2: green matter   20 kg (6 kg)

Balancing the biogas production and demand
Demand: 3.9 m³/d
Production: 3.0 m³/d

Changes/accommodations

On the demand side: 1 less lamp, reducing the demand to 3.55 m³
Production side: increasing the digester volume to 18 m³, resulting in a retention time of 75 days (f = 1.2) and a *daily gas yield of 3.6 m³*

Sizing the plant

Basic data (calculation for category 1)
Daily biomass: 150 kg/d
VS: 12 kg/d
TS-content: 12%
Soil temperature: max 31 °C, min. 22 °C, average 25 °C

Digester volume (Vd)

Retention time (chosen): RT = 60 d (at 25 °C, i.e. f = 1.0)
Substrate input: Sd = biomass + water
Digester TS-content: = 7% (chosen)
Daily water input: Wd = 100 kg
Sd = 100 + 150 = *250 l*
Digester volume: Vd = 250 l × 60 d = 15 000 = 15 m³

Daily biogas yield

G = kg/d VS × Gy,vs
     12 kg/d × 0.25 = 3.0 m³/d
G = kg/d biomass × Gy (moist)
     = 150 × 0.02 = 3.0 m³/d
G = number of animals × Gy per animal × d
     = 9 × 0.35   = 3.2 m³/d

Plant parameters

Digester volume: $Vd = 18 m^3$
Daily gas production: $G = 3.6 m^3$
Daily substrate input: Sd = 250 l
Spezific gas production:
$Gp = G : Vd$
$Gp = 3.6 (m^3/d) : 18 m^3 = 0.2 m^3/m^3$ Vd × d
Digester loading:
$Ld = TS/VS\text{-input} : Vd$
$Ld = 18 : 18 = 1.0$ kg TS/m³ Vd
$Ld = 12 : 18 = 0.7$ kg VS/m³ Vd
Gasholder volume:
$Vg = 1.6 m^3$, as calculated on the basis of:
consumption volume:
$Vgl = 0.175 m^3/h × 2$ flames × 3 h = 1.05 m³
Storage volume:
$Vg2 = 10 h × 0.15 m^3$ gas/h = 1.5 m³
$Vd : Vg = 18 : 1.6 = 11 : 1$

5. Biogas Technique

The design aspects dealt with below concentrate solely on the principles of construction and examples of simple biogas plants, i.e. plants:

— for small family farms requiring digester volumes of between 5 m^3 and 30 m^3,
— with no heating or temperature control,
— with no motor-driven agitators or slurry handling equipment,
— with simple process control,
— built with (at least mostly) local materials,
— built by local craftsmen.

5.1 Fundamental Principles, Parameters, Terms

Biochemical principles

The generation of biogas by organic conversion (anaerobic fermentation) is a natural biological process that occurs in swamps, in fermenting biomass and in intestinal tracts, particularly those of ruminants.

The symbiotic relationships existing between a wide variety of microorganisms leads, under air exclusion, to the degradation and

Fig. 5.1: Three-stage anaerobic fermentation (Source: Baader et. al 1978)
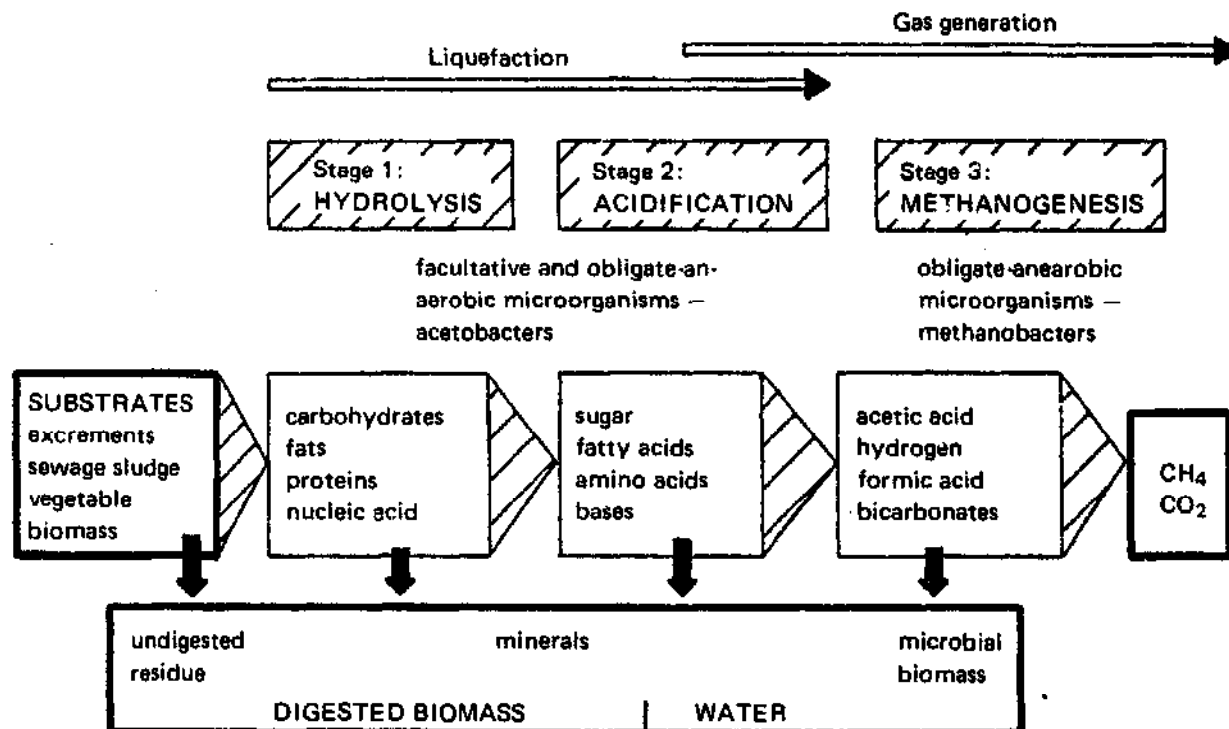
Table 5.1: Basic criteria for acetobacters (acid-forming bacteria) and methanobacters (methane-forming bacteria) (Source: OEKOTOP, compiled from various sources)

Criterion	Acetobacter	Methanobacter
Dominant microorganisms	facultative anaerobes	obligate anaerobes
Temperature range Optimum temperature	$3\,°C - 70\,°C$ approx. $30\,°C$	$3\,°C - 80\,°C$ approx. $35\,°C$ (sensitive to temperature fluctuations of $2-3\,°C$ or more)
pH range	acidic (3.0) 5.0–6.5	alkaline, 6.5–7.6
Growth rate	relatively short duplication period, usually less than 24 hours	relatively long duplication period (20–10 days)
End metabolites Mass transfer by ...	org. acids, H_2, CO_2 intensive mixing	CO_2, CH_4 gentle circulation
Medium	aqueous (water content > 60%)	
Sensitivity to cytotoxins	low	substantial
Requirements regarding nutrient composition	well-balanced supply of nutrients	
Special features	viable with or without free oxygen	viable only in darkness and in absence of free oxygen

mineralization of complex biomass in a sequence of intermeshing stages. The resultant biogas, consisting primarily of methane (CH_4) and carbon dioxide (CO_2) and the mineralized slurry constitute the ultimate catabolites of the participating bacteria and residual substances.

The process of anaerobic fermentation can be illustrated in the form of a three-stage model, as shown in figure 5.1.

Anaerobic fermentation converts the "volatile solids" (proteins, carbohydrates, fats). The "nonvolatile solids" are essential to the bacteria as "roughage" and minerals. Water serves simultaneously as the vital medium, solvent and transport vehicle.

Theoretical/laboratory data on maximum gas yields from various organic materials show that anaerobic fermentation is just as capable of achieving complete mineralization

Table 5.2: Energy potential of organic compounds (Source: Kaltwasser 1980)

Material	Biogas (l/kg)	CH_4 vol. fraction %	CO_2 vol. fraction %	Energy content (Wh/g)
Carbohydrates	790	50	50	3.78
Organic fats	1270	68	32	8.58
Protein	704	71	29	4.96

Table 5.3: Energetical comparison of aerobic and anaerobic fermentation (Source: Inden 1978)

Metabolite	aerobic	anaerobic
	energy fraction (%)	
Cytogenesis	60%	10%
Heat	40%	--
Methane	−	90%

as is the process of aerobic fermentation. Note: The theoretical maximum biogas yield can be ascertained by way of the basic composition of the biomass.

Characteristics that set anaerobic fermentation apart from aerobic fermentation (e.g. composting) include:

– fixation of biochemical energy in biogas
– little formation of new biomass
– low heat development
– fixation of minerals in the digested slurry.

It is important to know that anaerobic fermentation involves a steady-state flux of acetobacters and methanobacters, with the methanobacters, being more specialized and, hence, more sensitive, constituting the defining element. Any biogas plant can develop problems during the starting phase and in the case of overloading or uneven loading of the digester, and as a result of poisoning. This underlines the importance of cattle dung, which is rich in methanobacters and therefore serves as a good "starter" and "therapeutic instrument" in case of a disturbance.

With regard to technical exploitation, anaerobic fermentation must be regarded from a holistic point of view, since the "organism" is only capable of operating at optimum efficiency under a certain set of conditions. The process of anaerobic fermentation is quite variable and capable of stabilizing itself as long as a few basic parameters are adhered to.

Parameters and terminology of biomethanation

Feedstock/substrate:
As a rule, all watery types of biomass such as animal and human excrements, plants and organic wastewater are suitable for use in generating biogas. Wood and woody substances are generally unsuitable.

The two most important defining quantities of the biomethanation process are the substrate's solids content, i.e. *total solids* (TS, measured in kg TS/m^3) and its total organic solids content, i.e. *volatile solids* (VS, measured in kg VS/m^3). Both quantities are frequently stated as weight percentages.

The total-solids and water contents vary widely from substrate to substrate (cf. table 3.2 for empirical values). The most advantageous TS for the digester of a continuous-type biogas plant is 5–10%, compared to as much as 25% for a batch-operated plant. A TS of 15% or more tends to inhibit metabolism. Consequently, most substrates are diluted with water before being fed into the digester.

Substrate composition
All natural substrates may be assumed to have a nutritive composition that is adequately conducive to fermentation. Fresh green plants and agroindustrial wastewater, however, sometimes display a nutritive imbalance.

An important operating parameter is the ratio between carbon content (C) and nitrogen content (N), i.e. the C/N-ratio, which is considered favorable within the range 30 : 1 to 10 : 1. A C/N-ratio of less than 8 : 1 inhibits bacterial activity due to an excessive ammonia content.

Fermentation/digester temperature
As in all other microbial processes, the rate of metabolism increases along with the temperature. The fermentation/digester tem-

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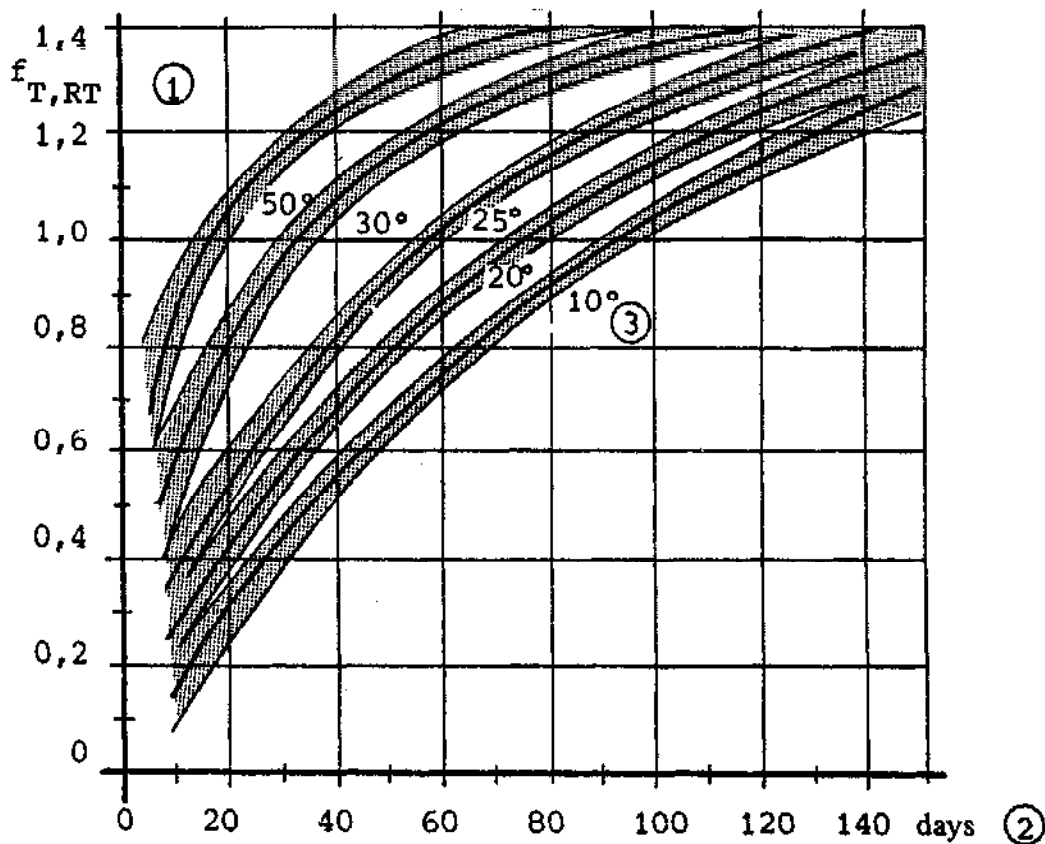
Fig. 5.2: Gas yield as a function of temperature and retention time ($f_{T,RT}$-curves). 1 $f_{T,RT}$: relative gas yield, serving as a multiplier for the average gas yields, e.g. those listed in table 3.5, 2 retention time (RT), 3 digester temperature (T), measured in °C (Source: OEKOTOP)

perature is of interest primarily in connection with the time required for complete fermentation, i.e. the retention time: the higher the temperature, the shorter the retention time. It has no effect on the absolute biogas yield, which is a constant that depends only on the type of biomass in the digester.

For reasons of operating economy, a somewhat shorter period of fermentation, the *technical retention time* (RT, t, measured in days) is selected such as to achieve an advantageous, temperature-dependent *relative digestion rate* (Dr, measured in %), also

referred to as the yield ratio, since it defines the ratio between the actual biogas yield and the theoretical maximum. The average agricultural biogas system reaches a Dr-value of 30–60%.

Volumetric digester charge/digester load

The volumetric charge, i.e. how much substrate is added per unit of digester volume each day (Vc, measured in m^3/m^3 Vd × d), is given by the chosen (technical) retention time (RT).

Table 5.4: Temperature ranges for anaerobic fermentation (Source: OEKOTOP, compiled from various sources)

Fermentation	Minimum	Optimum	Maximum	Retention time
Psycrophilic	4–10 °C	15–18 °C	25–30 °C	over 100 days
Mesophilic	15–20 °C	28–33 °C	35–45 °C	30–60 days
Thermophilic	25–45 °C	50–60 °C	75–80 °C	10–16 days

The digester load (Ld, measured in kg digested TS (VS)/m^3 Vd × day) serves as a measure of digester efficiency. The digester load is primarily dependent on four factors: substrate, temperature, volumetric burden and type of plant. For a typical agricultural biogas plant of simple design, the upper limit for Ld is situated at roughly 1.5 kg VS/m^3 × day. Excessive digester loading can lead to plant disturbances, e.g. a lower pH. In practice, the amount of TS/VS being added is frequently equated to the digester load.

Specific biogas yields / specific biogas production

The specific gas yield (Gy, measured in m^3 gas/kg TS (VS)) tells how much biogas can be drawn from a certain amount of biomass (cf. table 3.5 for empirical values). The rate of gas generation is naturally dependent on the digester temperature and retention time (cf. fig. 5.2).

The term specific gas production (Gp, measured in m^3 gas/m^3 Vd × day) supplements the above expression by defining the digester's biogas output.

pH/volatile acids

The pH is the central parameter of the biochemical bacterial environment.

As soon as the pH departs from the optimum range, bacterial activity is seriously impaired, resulting in lower gas yields, inferior gas composition (excessive CO_2 content) and obnoxious odor (H_2S — like rotten eggs).

Table 5.5: pH ranges for biomethanation (Source: OEKOTOP, compiled from various sources)

pH		
pH	7-7.2	optimum
pH	<6.2	acid inhibition
pH	>7.6	ammonia inhibition

Table 5.6: Substances with an inhibiting effect on biomethanation (Source: OEKOTOP, compiled from various sources)

Substance	Disruptive effects beginning (mg/l)
Copper	10 – 250
Calcium	8 000
Magnesium	3 000
Zinc	200 – 1 000
Nickel	350 – 1 000
Chromium	200 – 2 000
Cyanocompounds	25
Chlorinated hydrocarbons	traces
Herbicides	traces
Insecticides	traces

Toxins

Even a slight concentration of cytotoxins suffices to disrupt bacterial activity, with a resultant shift in pH, lower gas yield, higher CO_2 content and pronounced odor nuisance.

5.2 Design Principles of Simple Biogas Plants

The technical conception of biogas plants is determined by the aim of achieving optimal parameters for the biological process (cf. chapter 5.1).

That being so, the following operating requirements/limitations must be given due consideration:

– type and composition of organic material, which determines the choice of process

– given demand for biogas and fertilizer, in addition to the available substrate quantities, which determines the size of the biogas plant

– economy of labor input for building and operating the plants, including consideration of the necessary mechanical equipment.

The range of simple biogas plants includes the following basic types:

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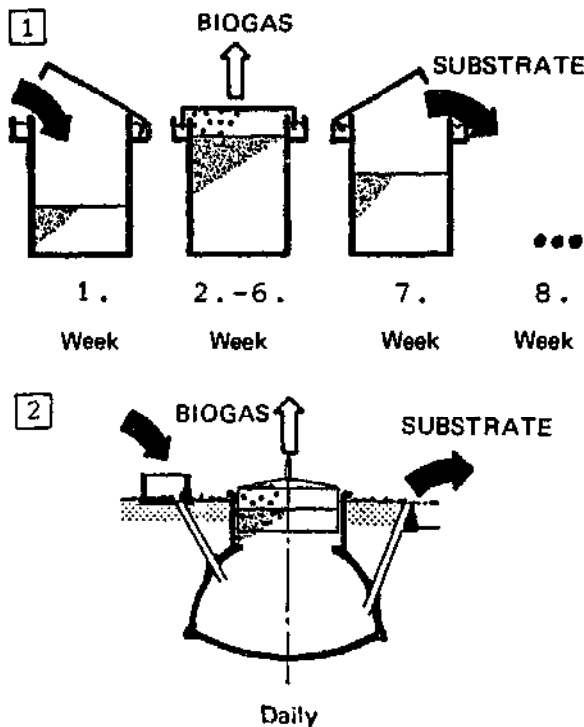
Fig. 5.3: The batch-feed principle (1) vs the continuousfeed principle (2) (Source: OEKOTOP)

Fig. 5.4: The fermentation channel (1) vs the complete-mixed digester (2) (Source: OEKOTOP)

Batch-type plants are thus referred to because they are charged with successive batches of organic material and a certain amount of seeding slurry to serve as starter. The digestion process is interrupted as soon as the rate of biogas production has slowed down to the point that continued digestion would be uneconomical. Then, the plant is cleaned out and refilled. To achieve a more or less uniform rate of biogas production, several digesters must be operated in parallel, i.e. filled at staggered intervals. Differentiation is made between semi-dry plants (operating on a total-solids content of more than 15%) and liquid plants.

Batch plants are suitable for digesting strawy, fibrous material with a high solids content, usually in areas with low annual precipitation, and for use as simple demonstration plants.

Continuous-feed plants are those in which there is a continuous throughflow of bio-

mass, resulting in a near-constant volume of slurry in the digester. In practice, such plants are fed once or twice each day. There are three main sub-versions:

— complete-mixed digesters
— fermentation channels and
— combinations of the two.

Fig. 5.5: Slurry flow for various configuration of feed, discharge and stirring. 1 Low inlet, outlet at top (beside the gasholder); 2 High inlet, low outlet (normal); 3 Low inlet, low outlet (with partition wall); 4 Vertical agitator; 5 Fixed-dome plant; F: Quality factor for thorough mixing and favorable throughflow conditions, normal situation = 100% (Source: OEKOTOP)
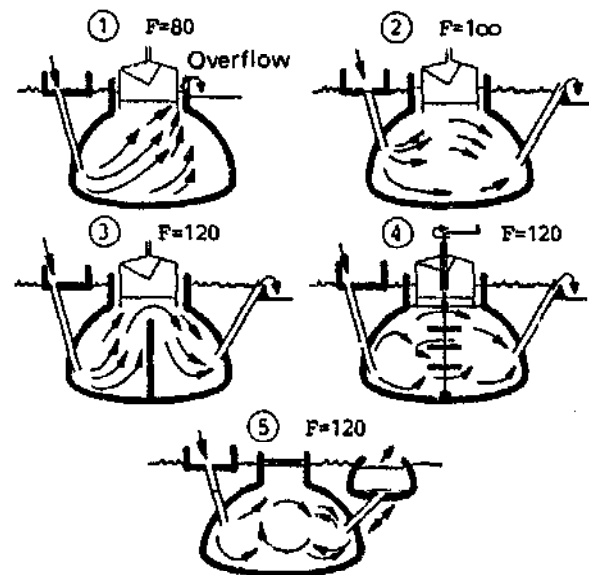
Photo 6: Floating-drum demonstration plant with external guide frame and direct infeed from the barn in Burundi (Source: OEKOTOP, BEP Burundi)

The advantage of continuous-feed plants is that the bacteria receive a regular supply of substrate and are therefore able to generate a more constant supply of biogas. The problem is that buoyant constituents tend to form a stiff layer of scum that impedes biogas production and may even plug up the plant. That drawback can be countered by installing suitable agitators and lengthening the retention time.

The digester inlet, outlet and, to the extent applicable, the agitator must be designed to work together in ensuring the proper retention time, i.e. to avoid short-circuit flow, because the gas production rate would otherwise stay well below the optimum level.

Continuous-feed biogas plants are sized on the basis of the desired retention time for the organic material, in combination with the digester load, which in turn is a function of the prevailing temperature and type of substrate (cf. chapter 4.3).

Photo 7: Family-sized floating-drum plant in Egypt (Source: OEKOTOP)
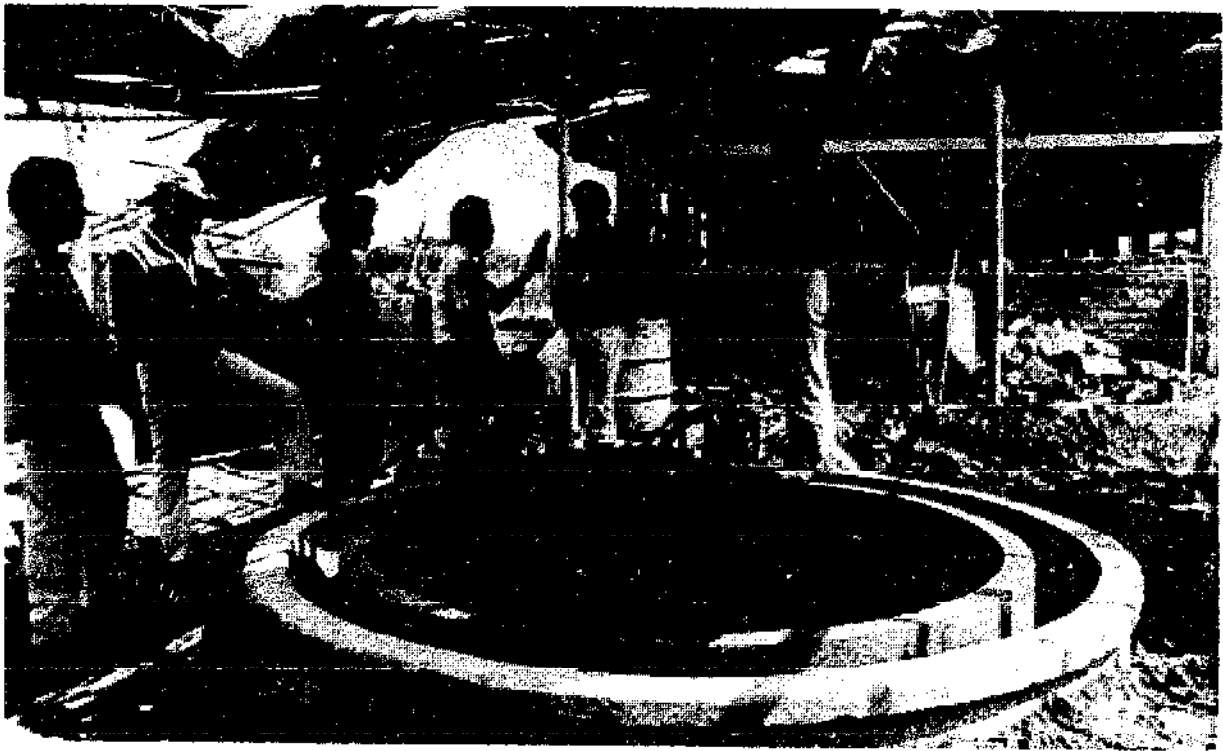
Photo 8: Water-jacket plant under construction in Colombia (Source: OEKOTOP)

Photo 9: Family-size biogas plant connected to toilet in India (Source: OEKOTOP)
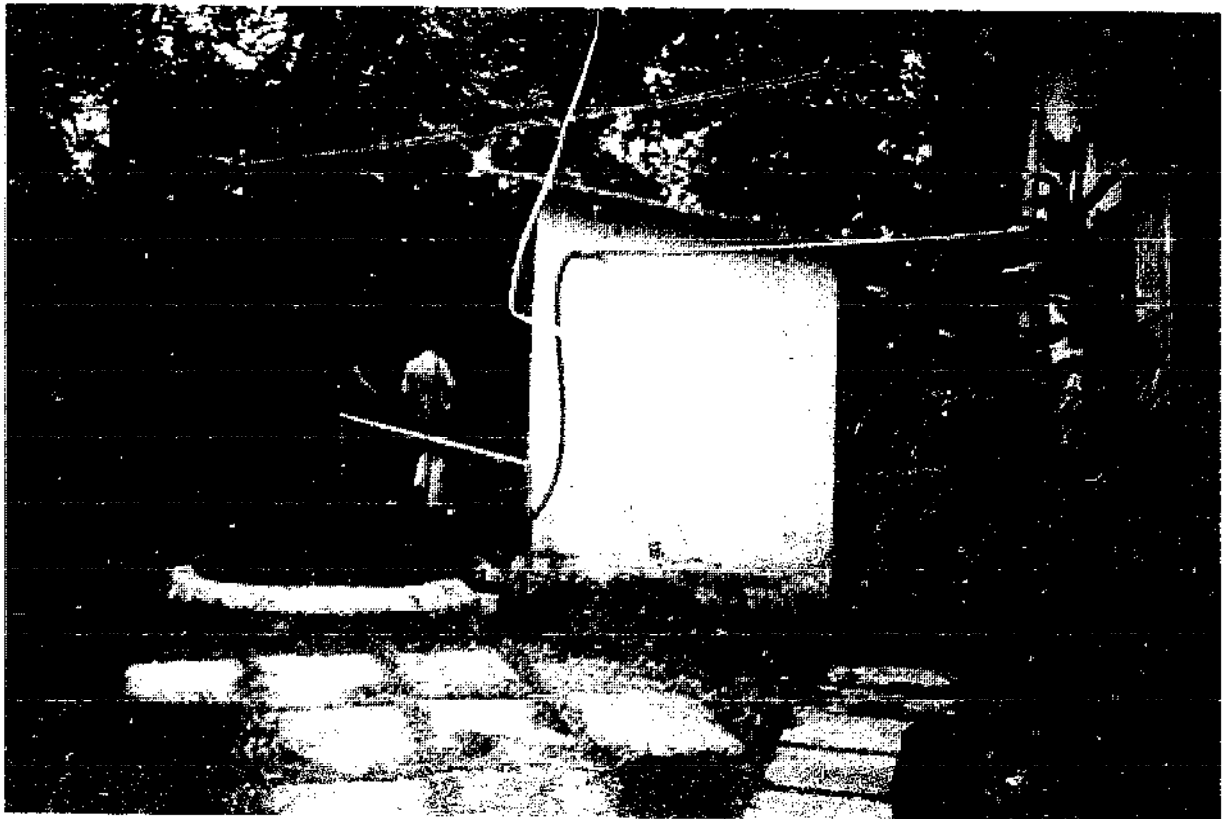
5.3 Biogas Plants of Simple Design

There are two basic types of tested biogas plants that have gained widespread acceptance in agricultural practice:

- floating-drum plants in which the metal gasholder floats on the digester, and
- fixed-dome plants in which gas storage is effected according to the displacement principle.

5.3.1 Floating-drum plants

A floating-drum biogas plant essentially consists of a cylindrical or dome-shaped digester and a movable, floating gasholder, or drum. The drum in which the biogas collects has an internal or external guide frame that provides stability and keeps the drum upright. Braces can be welded into the drum as a means of breaking up the scum layer when the drum is rotated. The digester is usually made of brick, concrete or quarrystone masonry with rendering, while the gasholder is normally made of metal.

Floating-drum plants are used chiefly for digesting animal and human excrements on a continuous-feed mode of operation, i.e. with daily input. They are used most frequently by:

- small-to-midsize family farms (digester size: 5–15 m³)
- institutions and large agroindustrial estates (digester size: 20–100 m³).

Advantages: Floating-drum plants are easy to understand and operate. They provide gas at a constant pressure, and the stored volume is immediately recognizable.

Drawbacks: The steel drum is relatively expensive and maintenance-intensive due to

Fig. 5.6: Floating-drum plant with internal guide frame. 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gasholder, 31 Guide frame, 4 Slurry store, 41 Discharge pipe, 5 Gas pipe, 51 Water trap (Source: Sasse 1984)

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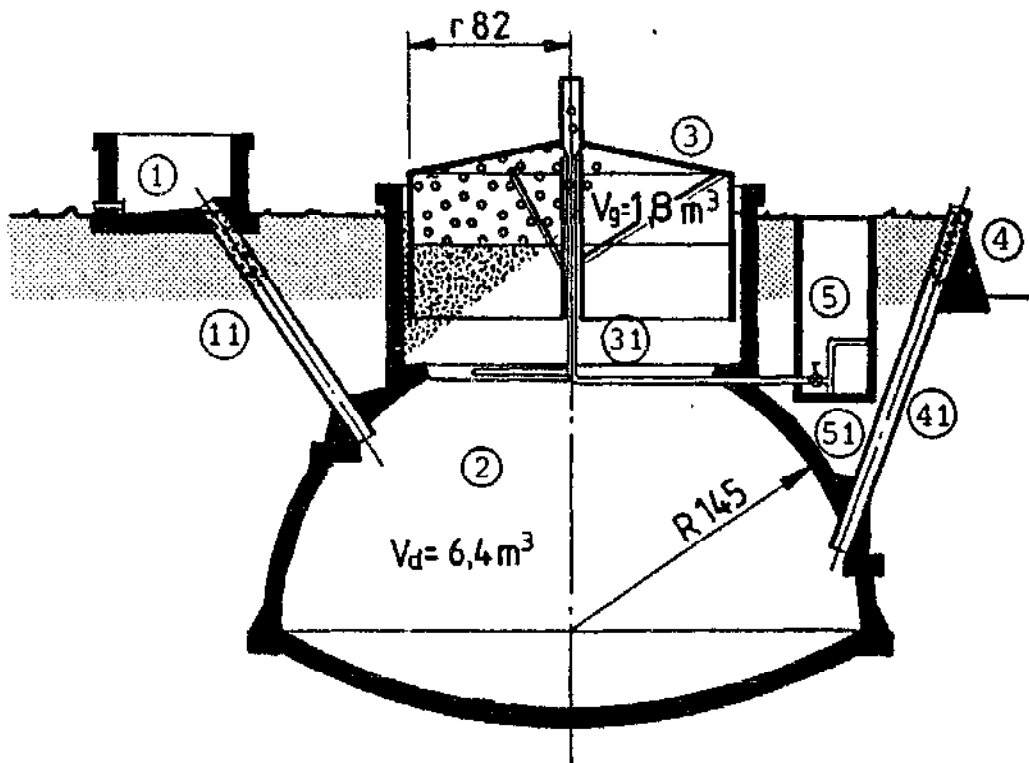
the necessity of periodic painting and rust removal. If fibrous substrates are used, the gasholder shows a tendency to get "stuck" in the resultant floating scum.

Floating-drum plants can be recommended as a mature, easy-to-operate, functionally capable means of producing biogas, particularly when reliability is deemed more important than inexpensiveness.

Floating-drum plants with gasholder in the digester (cf. fig. 5.6)

The dome shape is inherently sturdy, compact and material-sparing. The digester is easy to build, and the techniques can be learned by local craftsmen in a short time (cf. fig. 5.21).

Water-jacket plant (cf. fig. 5.7)

Water-jacket biogas plants are characterized by a long useful life and a more aesthetic appearance (no dirty gasholder). Due to their superior hygiene, they are recommended for use in the fermentation of night soil and for cases involving pronounced scumming, e.g. due to rapid evaporation, since the gasholder cannot get stuck in the scum. The extra cost of the masonry water jacket is relatively modest.

Cylindrical plant for quarrystone masonry and concrete (cf. fig. 5.8)

It is anything but easy to make a dome-shaped digester out of quarrystone masonry; it is much easier to build a concrete cylinder. In such cases, the classical (Indian)

Fig. 5.7: Water-jacket plant with external guide frame. 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gasholder, 31 Guide frame, 4 Slurry store, 5 Gas pipe (Source: Sasse 1984)
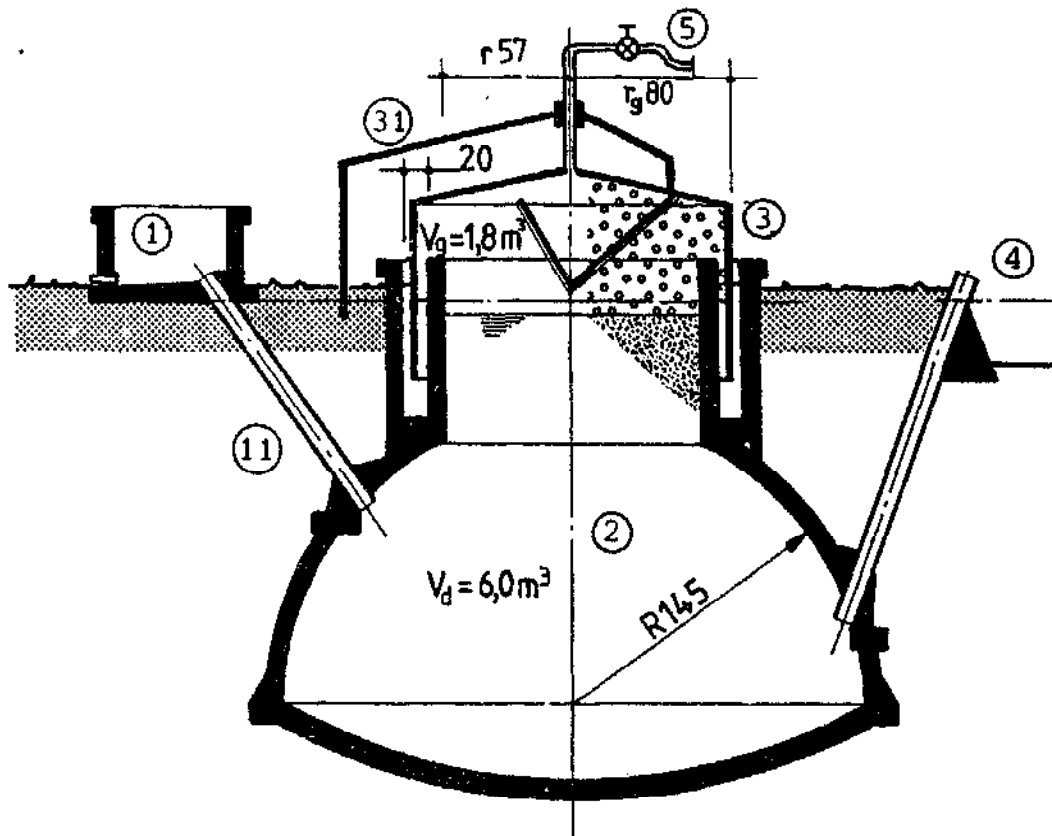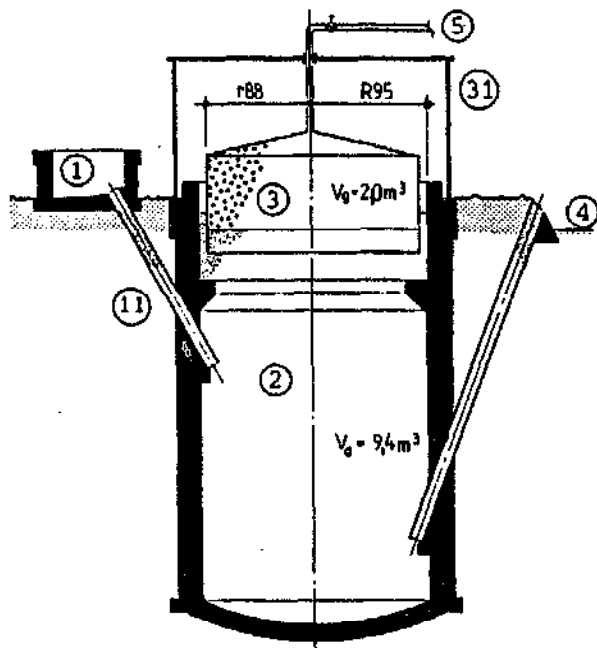
Fig. 5.8: Cylindrical plant design for quarrystone masonry construction. 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gasholder, 31 Guide frame, 4 Slurry store, 5 Gas pipe (Source: KVIC)

version with a cylindrical digester is quite practical. Note: Quarrystone masonry consumes a lot of mortar.

5.3.2 Fixed-dome plants

A fixed-dome plant comprises a closed, dome-shaped digester with an immovable, rigid gasholder and a displacement pit. The gas collects in the upper part of the digester. Gas production increases the pressure in the digester and pushes slurry into the displacement pit. When gas is extracted, a proportional amount of slurry flows back into the digester.

The gas pressure does not remain constant in a fixed-dome plant, but increases with the amount of stored gas. Consequently, a special-purpose pressure controller or a separate floating gasholder is needed to achieve a constant supply pressure. The digesters of such plants are usually made of masonry, with paraffin or bituminous paint applied to

the gas-filled area in order to make it gastight.

Fixed-dome plants can handle fibrous substances in combination with animal excrements, since the motion of the substrate breaks up the scum each day. The plant is a continous-feed type, but can accept several days' worth of substrate at a time, if the displacement pit is large enough.

Fixed-dome plants must be covered with earth up to the top of the gas-filled space as a precautionary measure (internal pressure up to 0.1—0.15 bar). As a rule, the size of the digester does not go beyond 20 m^3, corresponding to a gasholder volume of 3—4 m^3. The earth cover makes them suitable for colder climates, and they can be heated as necessary.

Advantages: Fixed-dome plants are characterized by low initial cost and a long useful life, since no moving or rusting parts are involved. The basic design is compact and well-insulated.

Drawbacks: Masonry is not normally gastight (porosity and cracks) and therefore requires

Fig. 5.9: Basic function of a fixed-dome biogas plant. 1 Mixing pit, 2 Digester, 3 Gasholder, 4 Displacement pit, 5 Gas pipe (Source: OEKOTOP)

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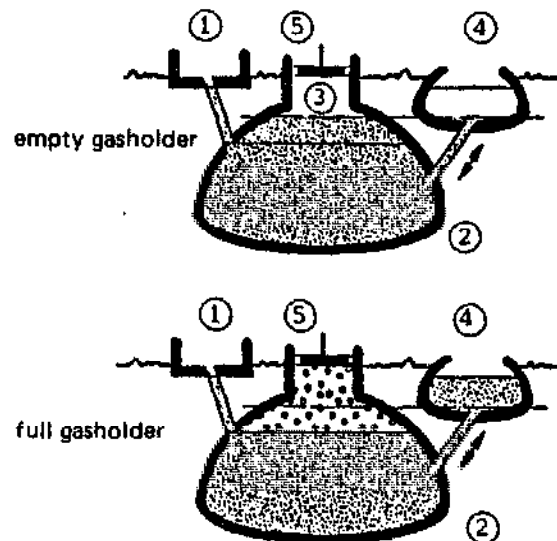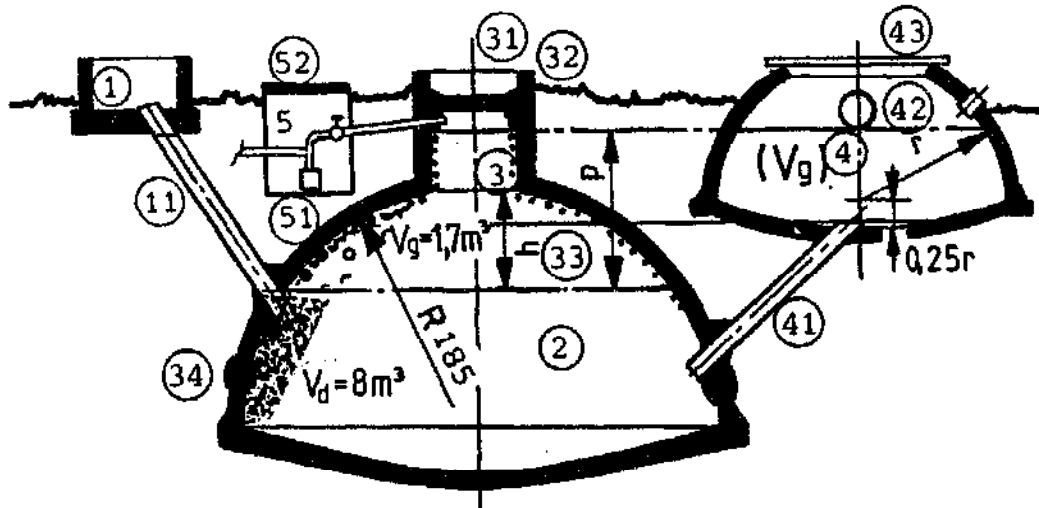
Fig. 5.10: Fixed-dome plant with central entry hatch. 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gas holder, 31 Entry hatch, 32 Gas cover, 33 Seal coating, 34 Rated break ring, 4 Displacement pit, 41 Outlet pipe, 42 Overflow, 43 Cover, 5 Gas pipe, 51 Water trap, 52 Cover (Source: Sasse 1984 / BEP Tanzania 1987 / OEKOTOP)

the use of special sealants. Cracking often causes irreparable leaks. Fluctuating gas pressure complicates gas utilization, and plant operation is not readily understandable.

Fixed-dome plants are only recommended in cases where experienced biogas technicians are available for building them, and when the user is amply familiar with how the plant operates.

Fixed-dome plant with central entry hatch (cf. fig. 5.10)

The digester has the form of a hemispherical dome which is easy to build. Floating scum can be removed from the full digester through the central entry hatch.

Fig. 5.11: Fixed-dome plant with suspended dome. 1 Mixing pit, 11 Fill pipe, 2 Digester, 21 Digester rendering, 3 Gas holder, 31 Entry hatch, 32 Gas cover, 33 Seal coating, 34 Dome foundation, 35 Dome masonry, 4 Displacement pit, 41 Outlet pipe, 42 Overflow, 43 Cover, 5 Gas pipe (Source: BEP Tanzania 1987 / OEKOTOP)

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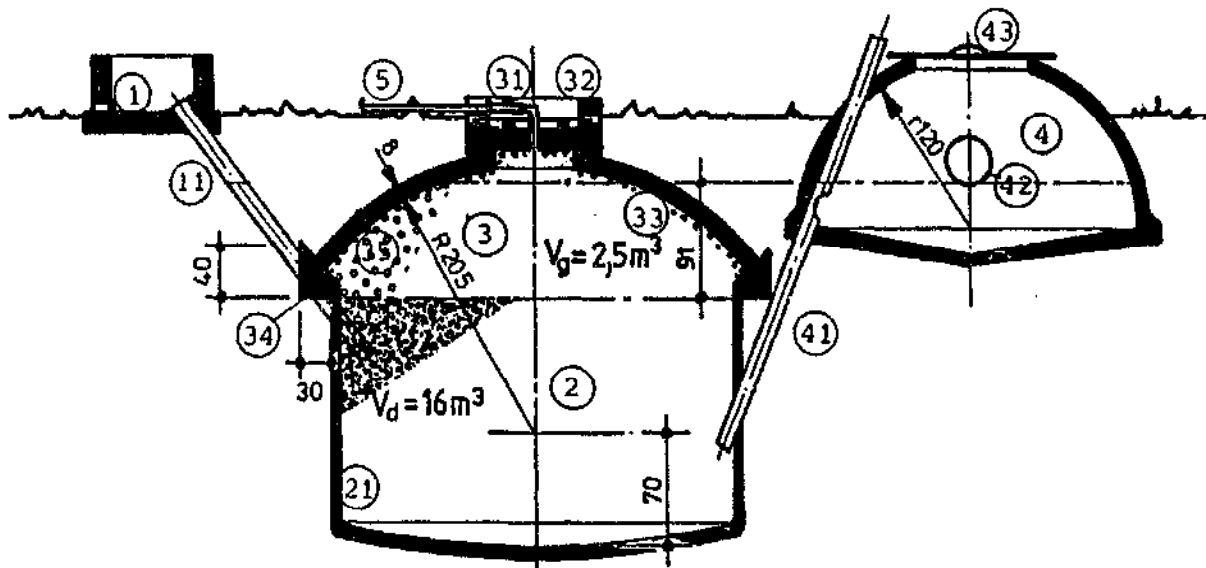
Fixed-dome plant with suspended dome
(cf. fig. 5.11)

Providing a separate foundation for the gas dome yields a statically advantageous, material-saving configuration that is very well suited for fixed-dome plants of ample size. The dome's foundation helps prevent cracking due to tensile stress, and the digesting space is made less expensive, since it can be built of thinner masonry, ferrocement rendering or — in the case of impervious soil — even left unlined.

5.3.3 Other types of construction

In addition to the two most familiar types of biogas plant, as described above, a selection of special-purpose and otherwise promising designs are briefly presented below.

Inflatable balloon plants (cf. fig. 5.12)

Inflatable biogas plants consist of a heat-sealed plastic or rubber bag (balloon), the top and bottom parts of which serve as the gasholder and digester, respectively. The requisite gas pressure is achieved by weighting down the bag. Since the material has to be weather-resistant, specially stabilized, rein-

forced plastic or synthetic caoutchouc is given preference. The useful life amounts to 2–5 years.

Advantages: Standardized prefabrication at low cost; shallow installation suitable for use in areas with a high groundwater table.

Drawbacks: Low gas pressure requires extra weight burden; scum cannot be removed. The plastic balloon has a relatively short useful life, is susceptible to damage by mechanical means, and usually not available locally. In addition, local craftsmen are rarely in a position to repair a damaged balloon.
Inflatable biogas plants are recommended, if local repair is or can be made possible and the cost advantage is substantial.

Earth-pit plants (cf. fig. 5.13)

Masonry digesters are not necessary in stable soil (e.g. laterite). It is sufficient to line the pit with a thin layer of cement (netting wire fixed to the pit wall and rendered) in order to prevent seepage. The edge of the pit is reinforced with a ring of masonry that also serves as anchorage for the gasholder. The gasholder can be made of metal or plastic

Fig. 5.12: Horizontal balloon-type biogas plant. 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gasholder, 4 Slurry store, 41 Outlet pipe, 5 Gas pipe, 51 Water trap, 6 Burden, 61 Guide frame (Source: OEKOTOP)
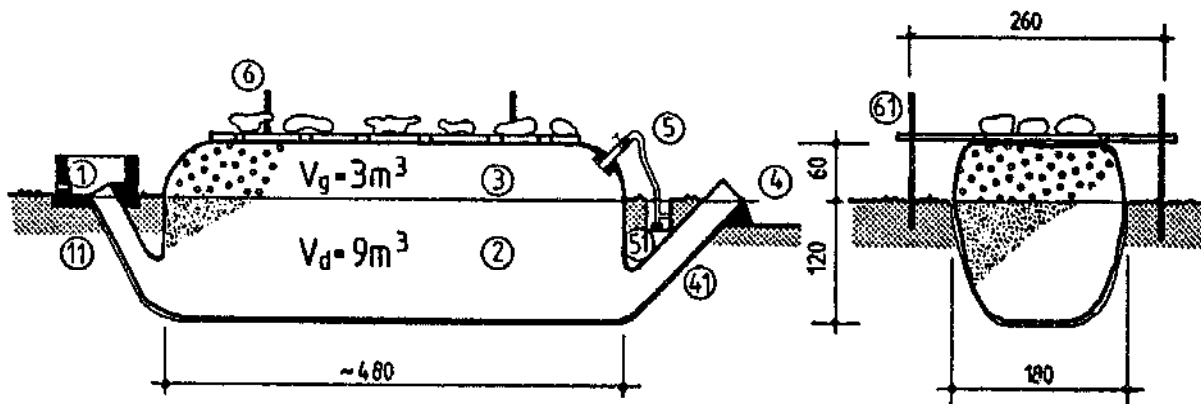
Photo 10: Fixed-dome biogas plant. Inlet at left, entry hatch/gas outlet at center, displacement pit and slurry store at right (Source: OEKOTOP)

Photo 11: A nearly finished fixed-dome plant in combination with cattle shelter (Source: OEKOTOP, BEP Tanzania)
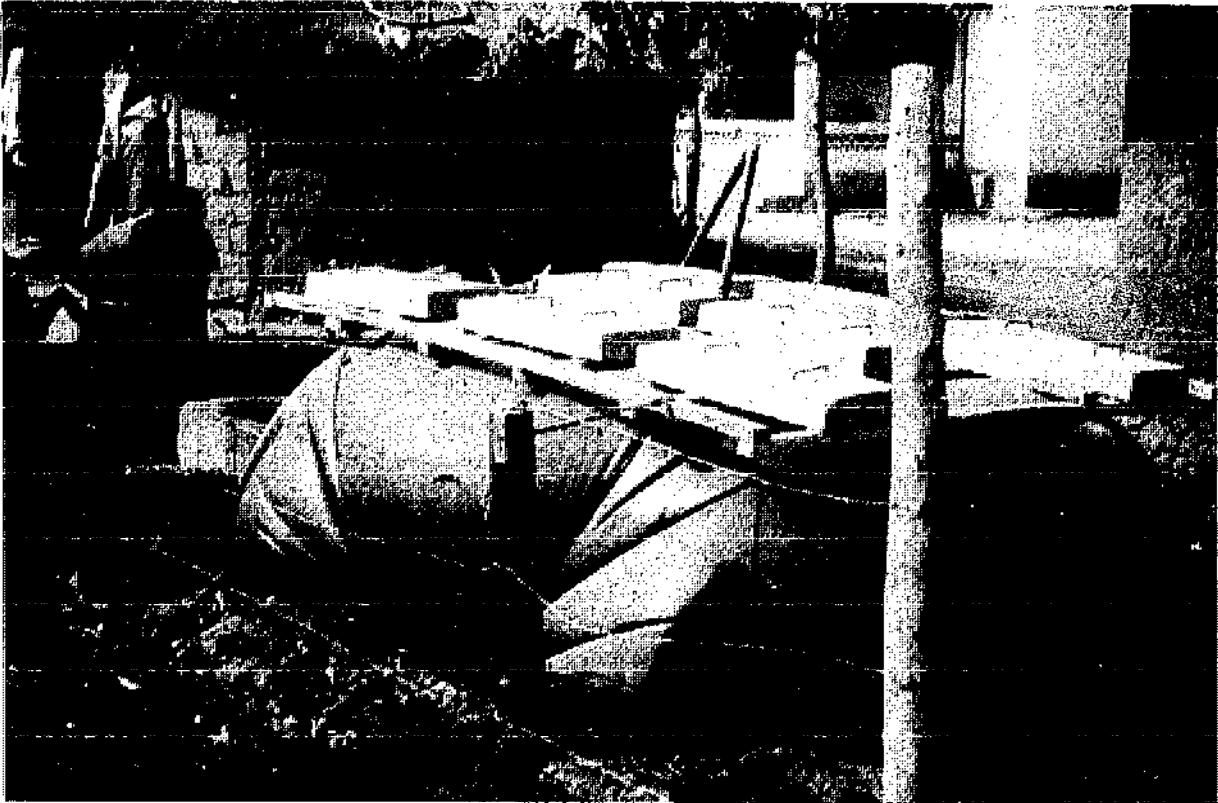
Photo 12: Earth-pit plant with plastic-sheet gasholder in Côte d'Ivoire (Source: OEKOTOP)

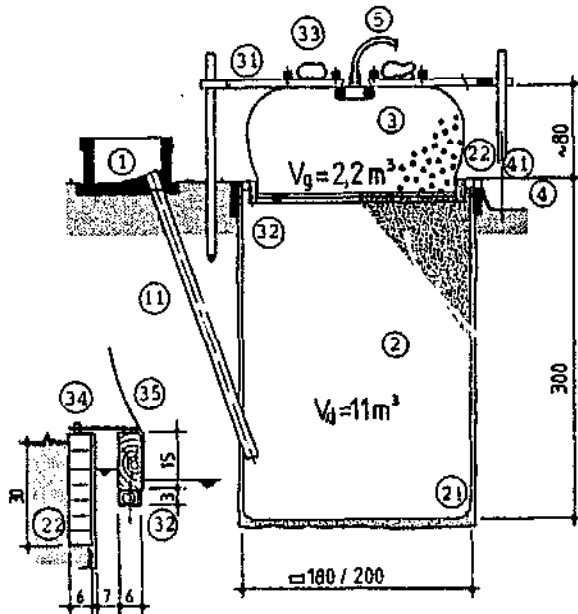Photo 13: Biogas plant with ferrocement gasholder in India (Source: Sasse)

Fig. 5.13: Earth-pit plant with plastic-sheet gasholder. 1 Mixing pit, 11 Fill pipe, 2 Digester, 21 Rendering, 22 Peripheral masonry, 3 Plastic-sheet gasholder, 31 Guide frame, 32 Wooden frame, 33 Weight, 34 Frame anchorage, 35 Plastic sheeting, 4 Slurry store, 41 Overflow, 5 Gas pipe (Source: OEKOTOP)

sheeting. If plastic sheeting is used, it must be attached to a quadratic wooden frame that extends down into the slurry and is anchored in place to counter its buoyancy. The requisite gas pressure is achieved by placing weights on the gasholder. An overflow point in the peripheral wall serves as the slurry outlet.

Advantages: Low cost of installation (as little as 1/5th as much as a floating-drum plant), including high potential for self help.

Drawbacks: Short useful life, serviceable only in suitable, impermeable types of soil. Earth-pit plants can only be recommended for installation in impermeable soil located above the groundwater table. Their construction is particularly inexpensive in connection with plastic sheet gasholders.

Fig. 5.14: Ferrocement biogas plant. 1 Mixing pit, 11 Fill pipe, 2 Digester, 21 Backfill soil, 22 Ferrocement, i.e. rendered lathing on surrounding soil, 3 Ferrocement gasholder, 31 Guide frame, 41 Outlet pipe, 5 Gas pipe, 51 Water trap (Source: OEKOTOP/BEP Caribbean 1986)

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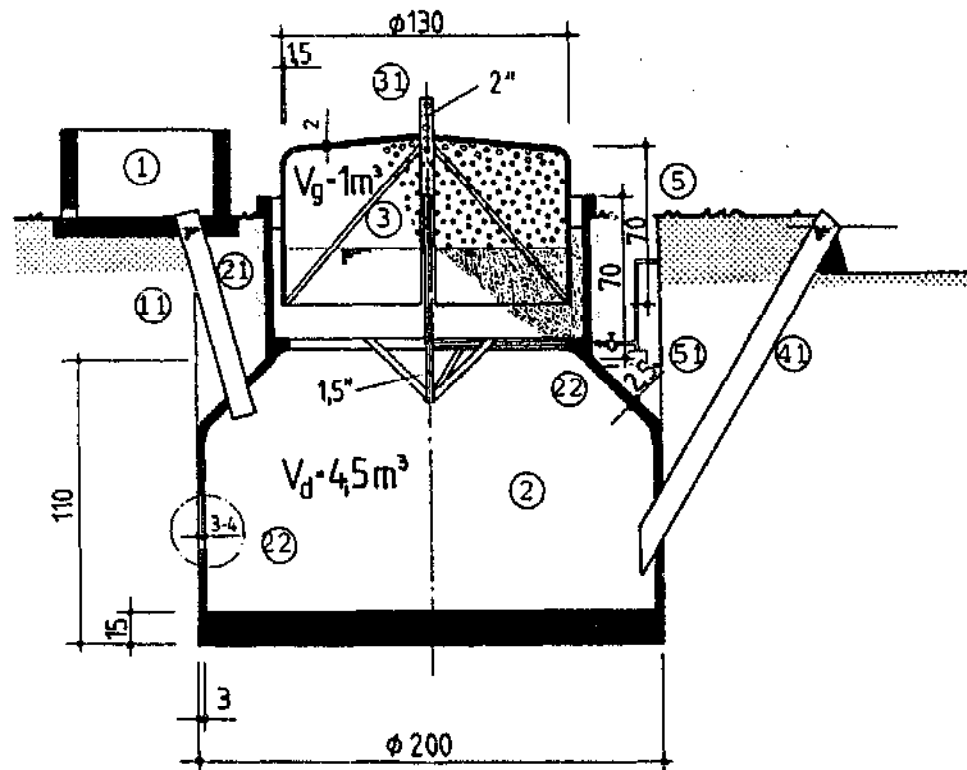
Ferrocement plants (cf. fig. 5.14)

The ferrocement type of construction can be executed as either a self-supporting shell or an earth-pit lining. The vessel is usually cylindrical. Very small plants ($Vd < 6$ m^3) can be prefabricated. As in the case of a fixed-dome plant, the ferrocement gasholder requires special sealing measures (provenly reliable: cemented-on aluminum foil).

Advantages: Low cost of construction, especially in comparison with potentially high cost of masonry for alternative plants.

Drawbacks: Substantial consumption of necessarily good-quality cement; participating craftsmen must meet high standards; uses substantial amounts of steel; construction technique not yet adequately time-tested; special sealing measures for the gasholder.
Ferrocement biogas plants are only recommended in cases where special ferrocement know-how is available.

Horizontal plants (cf. fig. 5.15)

Horizontal biogas plants are usually chosen when shallow installation is called for (groundwater, rock). They are made of masonry or concrete.

Advantages: Shallow construction despite large slurry space.

Drawbacks: Problems with gas-space leakage, difficult elimination of scum.

Plants with separate gasholders

Masonry dome plants are sometimes equipped with separate gasholders. That approach always involves substantial extra cost and therefore is rarely recommended. Plants with separate gasholders are justifiable, when the points of gas consumption are a considerable distance away from the digester (at least 100 m).
Alternatively, a separate gasholder could be useful for restoring the utility value of, say, a fixed-dome plant that has been found to leak at an elevated pressure level.

Fig. 5.15: Horizontal biogas plant (KVIC shallow design). 1 Mixing pit, 11 Fill pipe, 2 Digester, 3 Gasholder, 31 Guide frame, 4 Slurry store, 41 Outlet pipe, 5 Gas pipe, 51 Water trap (Source: OEKOTOP / KVIC 1978)
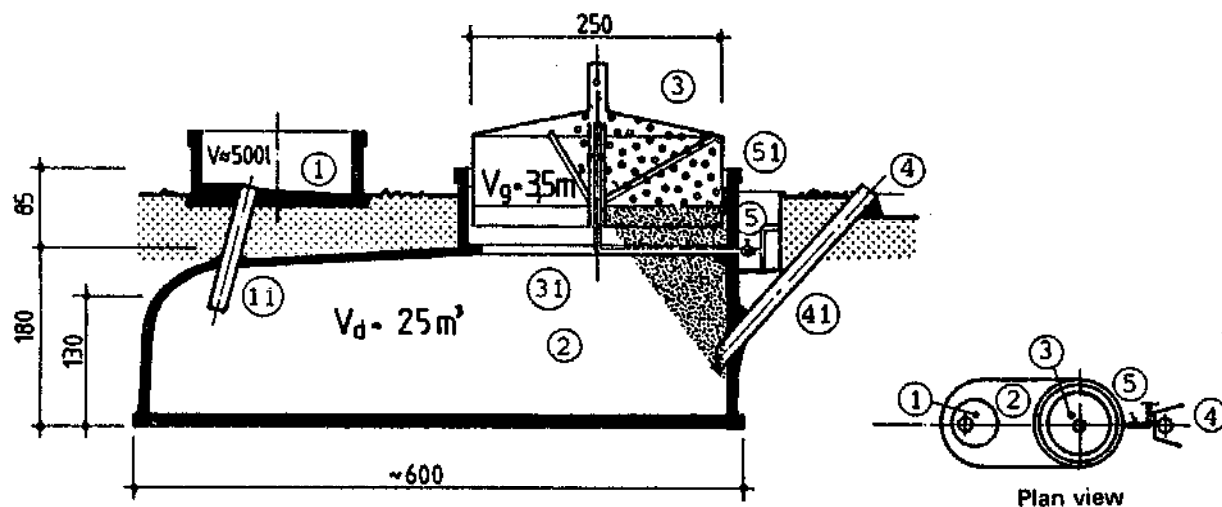

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Table 5.7: Comparison of various plant designs (Source: OEKOTOP)

Design: Criteria:	Floating-drum	Water-jacket	Fixed-dome
Design principle	continuous-feed, mixed digester	continuous-feed, mixed digester	continuous-feed, mixed digester with slurry store
Main components	masonry digester, floating metal gasholder	masonry digester, floating metal gasholder in sep. water jacket	masonry digester/gasholder with displacement pit
Preferred substrates	animal excrements, with or without vegetable waste	animal excrements with or without vegetable waste	animal excrements plus vegetable waste
Anticipated useful life	8–12 years	10–15 years	12–20 years
Digester volume (Vd)	6–100 m³	6–100 m³	6–20 m³
Suitability: – advantages	easy construction and operation, uniform gas pressure, mature technology	very reliable, easy construction and operation, uniform gas pressure, long useful life, mature technology	low cost of construction, long useful life, well-insulated
– drawbacks	metal gasholder can rust	expensive	sealing of gasholder, fluctuating gas pressure

– All biogas plants require careful, regular inspection/monitoring of their gas-containing components –

	Floating-drum	Water-jacket	Fixed-dome
Operation and maintenance	simple and easy; regular painting of metal gasholder	simple and easy; regular painting of metal gasholder	easy after careful familiarization
Daily gas-output (m³ gas/m³ Vd) (depends on substrate composition; here: cattle dung)	0.3–0.6	0.3–0.6	0.2–0.5
Cost elements Comparison factor	metal gasholder, digester 100	metal gasholder, digester 120	combined digester/ gasholder, Excavation 60–90
Recommended uses	fully developed, reliable familysize system	like floating-drum, plus longer useful life and operational reliability (incl. operation with night soil)	inexpensive equipment, good for agroresidue, extensive building experience required
Suitability for dissemination	+	++	+

++ highly recommended, + recommended with certain reservations

balloon-type	Earth pit	Ferrocement	Horizontal (shallow)
continuous-feed, fermentation channel	continuous-feed, mixed digester	continuous-feed, mixed digester	continuous-feed, fermentation channel
integrated digester/gas-holder made of plastic sheeting	earth pit as digester, plastic gasholder	ferrocement digester, gasholder made of metal or ferrocement	masonry digester, floating metal gasholder (or separate)
animal excrements only	animal excrements only	animal excrements, with or without vegetable waste	animal excrements, with or without vegetable waste
2–5 years	2–5 years	6–10 years	8–12 years
4–100 m³	4–500 m³	4–20 m³	20–150 m³
prefab. construction, easy operation	extremely inexpensive, easy operation	potentially inexpensive construction, long useful life, easy operation, reliable	shallowness, easy operation
in-situ processing and short useful life (2-5 years) of plastic material, low gas pressure	same as with plastic gas-holder, plus soil perme-ability	ferrocement construction not yet adequately time-tested	expensive, metal gasholder
easy; regular control of gas-pressure weights	easy	simple and easy	simple and easy
0.3–0.8	0.1–0.5	0.3–0.6	0.3–0.7
plastic sheeting	plastic sheeting	concrete (cement), lathing	digester, metal gasholder
20–110	20–40	70–90	90
mostly for large-scale plants and fast solutions	very inexpensive plant	like floating-drum but requires experience in ferrocement construction	medium-size system where shallowness is required
o	o	–	o

o recommended under certain circumstances, – not yet ready for recommendation

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5.4 Design and Construction of Plant Components

Biogas plants of simple design consist of the following main components:
- mixing pit
- inlet/outlet (feed/discharge pipes)
- digester
- gasholder
- slurry store.

Depending on the available building material and type of plant under construction, different variants of the individual components are possible.

5.4.1 Mixing pit

In the mixing pit, the substrate is diluted with water and agitated to yield a homogeneous slurry.

The fibrous material is raked off the surface, and any stones or sand settling to the bottom are cleaned out after the slurry is admitted to the digester.

The useful volume of the mixing pit should amount to 1.5–2 times the daily input quantity. A rock or wooden plug can be used to close off the inlet pipe during the mixing process. A sunny location can help warm the contents before they are fed into the digester in order to preclude thermal shock due to the cold mixing water. In the

Table 5.8: Common substrate mixing ratios (Source: OEKOTOP, compiled from various sources)

Type of substrate	Substrate : Water	
Fresh cattle manure	1	: 0.5 –1
Semi-dry cattle dung	1	: 1–2
Pig dung	1	: 1–2
Cattle and pig dung from a floating removal system	1	: 0
Chicken manure	1	: 4–6
Stable manure	1	: 2–4
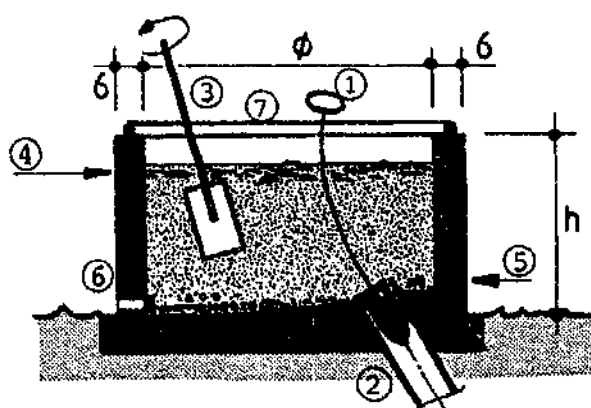
Fig. 5.16: Mixing pit. 1 Plug, 2 Fill pipe, 3 Agitator, 4 Fibrous material, 5 Sand, 6 Drain, 7 Screen cover (Source: OEKOTOP)

case of a biogas plant that is directly connected to animal housing, it is advisable to install the mixing pit deep enough to allow installation of a floating gutter leading directly into the pit. Care must also be taken to ensure that the low position of the mixing pit does not result in premature digestion and resultant slurry formation. For reasons of hygiene, toilets should have a direct connection to the inlet pipe.
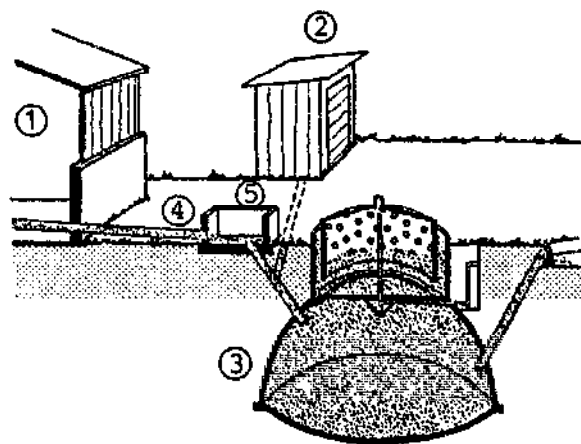

Fig. 5.17: Mixing pit, gutter and toilet drain pipe. 1 Barn, 2 Toilet, 3 Biogas plant, 4 Feed gutter (2% gradient), 5 Mixing pit (Source: OEKOTOP)

5.4.2 Inlet and outlet

The inlet (feed) and outlet (discharge) pipes lead straight into the digester at a steep angle. For liquid substrate, the pipe diame-
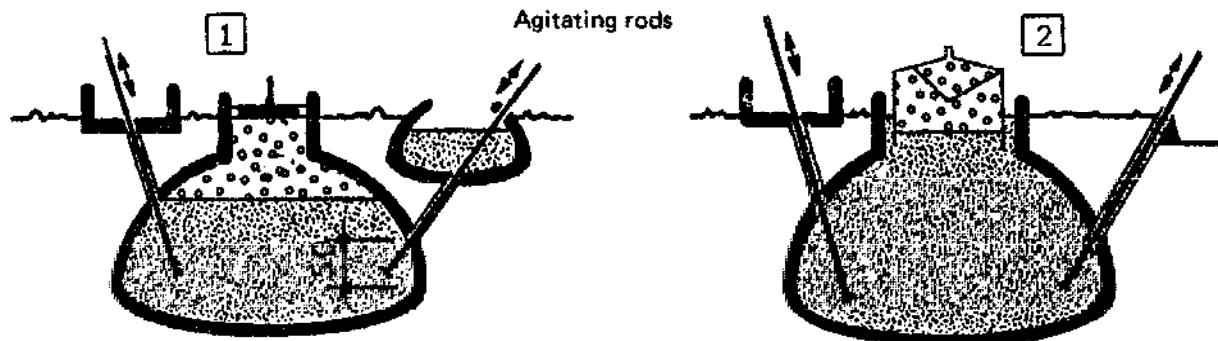
Fig. 5.18: Inlet and outlet for fixed-dome (1) and floating-drum plants (2) (Source: OEKOTOP)

ter should be 10–15 cm, while fibrous substrate requires a diameter of 20–30 cm. Plastic or concrete pipes are preferred.

Note:

— Both the inlet pipe and the outlet pipe must be freely accessible and straight, so that a rod can be pushed through to eliminate obstructions and agitate the digester contents;

— The pipes should penetrate the digester wall at a point below the slurry level. The points of penetration should be sealed off and reinforced with mortar.

— The inlet pipe ends higher than the outlet pipe in the digester in order to promote more uniform throughflow. In a fixed-dome plant, the inlet pipe defines the bottom limit of the gasholder, thus providing overpressure relief.

— In a floating-drum plant, the end of the outlet pipe determines the digester's slurry level.

5.4.3 Digester

Design

The digester of a biogas plant must accommodate the substrate and bacterial activity, as well as fulfill the following structural functions:

— accept the given static forces
— provide impermeability to gas and liquids
— be durable and resistant to corrosion

As a rule, the digesters of simple biogas plants are made of masonry or concrete. Such materials are adequately pressure-resistant, but also susceptible to cracking as a result of tensile forces.

The following forces act on the digester:

— external active earth pressures (pE), causing compressive forces within the masonry

— internal hydrostatic and gas pressures (pW), causing tensile stress in the masonry.

Fig. 5.19: Forces acting on a spherical-dome digester (Source: OEKOTOP)
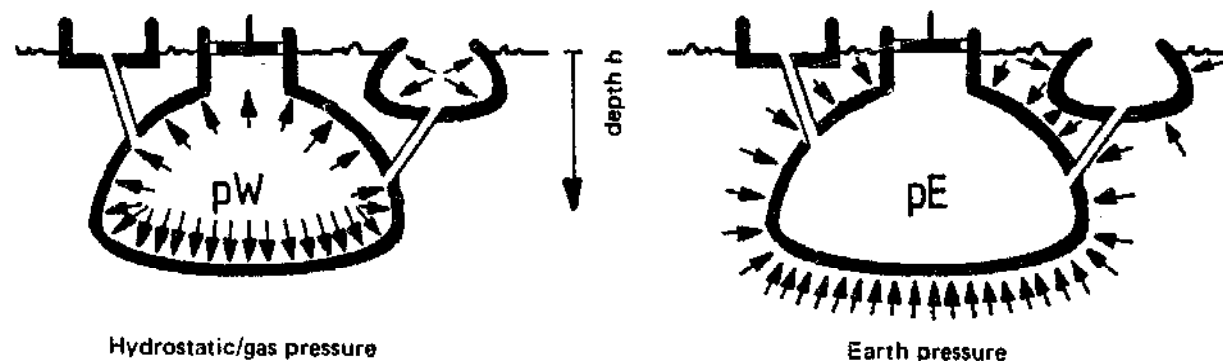
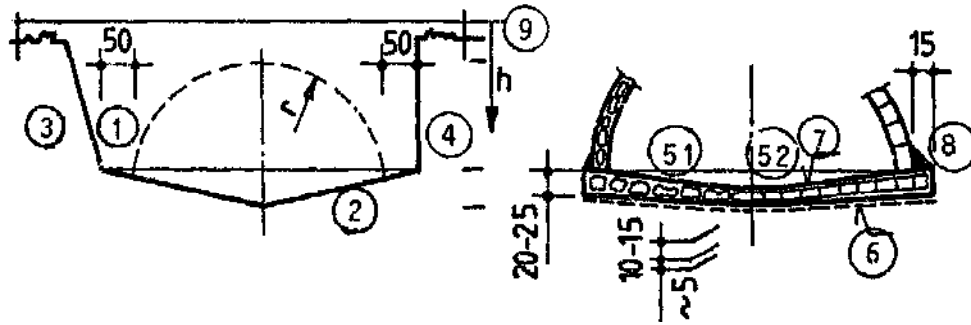Hydrostatic/gas pressure   Earth pressure

Fig. 5 20: Level line, excavation and foundation. 1 Workspace, 2 Inclination of conical foundation, 3 Sloping excavation. 4 Vertical excavation, 51 Quarrystone foundation, 52 Brick foundation, 6 Packing sand, 7 Mortar screed, 8 Foot reinforcement for fixed-dome plant. 9 Level line (Source: OEKOTOP / Sasse 1984)

Thus, the external pressure applied by the surrounding earth must be greater at all points than the internal forces ($pE > pW$). For the procedure on how to estimate earth force and hydrostatic forces, please refer to chapter 10.1.4.

Round and spherical shapes are able to accept the highest forces – and do it uniformly. Edges and corners lead to peak stresses and, possibly, to tensile stresses and cracking. Such basic considerations suggest the use of familiar cylindrical and dome designs allowing:

-- inexpensive, material-sparing construction based on modest material thicknesses

– a good volume/surface ratio and

– better (read: safe) stability despite simple construction.

The dome foundation has to contend with the highest loads. Cracks occurring around the foundation can spread out over the entire dome, but are only considered dangerous in the case of fixed-dome plants. A rated break ring can be provided to limit cracking.

Groundwork

The first step of building the plant consists of defining the plant level line with a taut string. All important heights and depths are referred to that line.

Photo 14: Excavation for a biogas plant (Source: OEKOTOP)

Photo 15: Installing the neck masonry of a fixed-dome (Source: OEKOTOP)

Photo 16: Checking the digester masonry with a trammel (Source: OEKOTOP)

Photo 17: Guide frame for the gasholder of a floating-drum plant (Source: OEKOTOP)

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Excavation

The pit for the biogas plant is excavated by hand in the shape of a cylindrical shaft. The shaft diameter should be approx. 2 × 50 cm larger than that of the digester. If the soil is adequately compact and adhesive, the shaft wall can be vertical. Otherwise it will have to be inclined. The overburden, if reusable, is stored at the side and used for backfilling and compacting around the finished plant.

Foundation

The foundation slab must be installed on well-smoothed ground that is stable enough to minimize settling. Any muddy or loose subsoil (fill) must be removed and replaced by sand or stones. The bottom must have the shape of a shallow inverted dome to make it more stable and rigid than a flat slab. Quarrystones, bricks and mortar or concrete can be used as construction materials. Steel reinforcing rods are only necessary for large plants, and then only in the form of peripheral ties below the most heavily burdened part, i.e. the dome foundation.

Dome

The dome of the biogas plant is hemispherical with a constant radius. Consequently, the masonry work is just as simple as for a cylinder and requires no falsework. The only accessory tool needed is a trammel.

The dome masonry work consists of the following steps:

Fig. 5.21: Construction of a spherical dome from masonry. 1 Dome/masonry, 2 Establishing the center-point, 3 Trammel, 4 Brick clamp with counterweights, 5 Backfill (Source: Sasse 1984)

Trammel   Masonry details
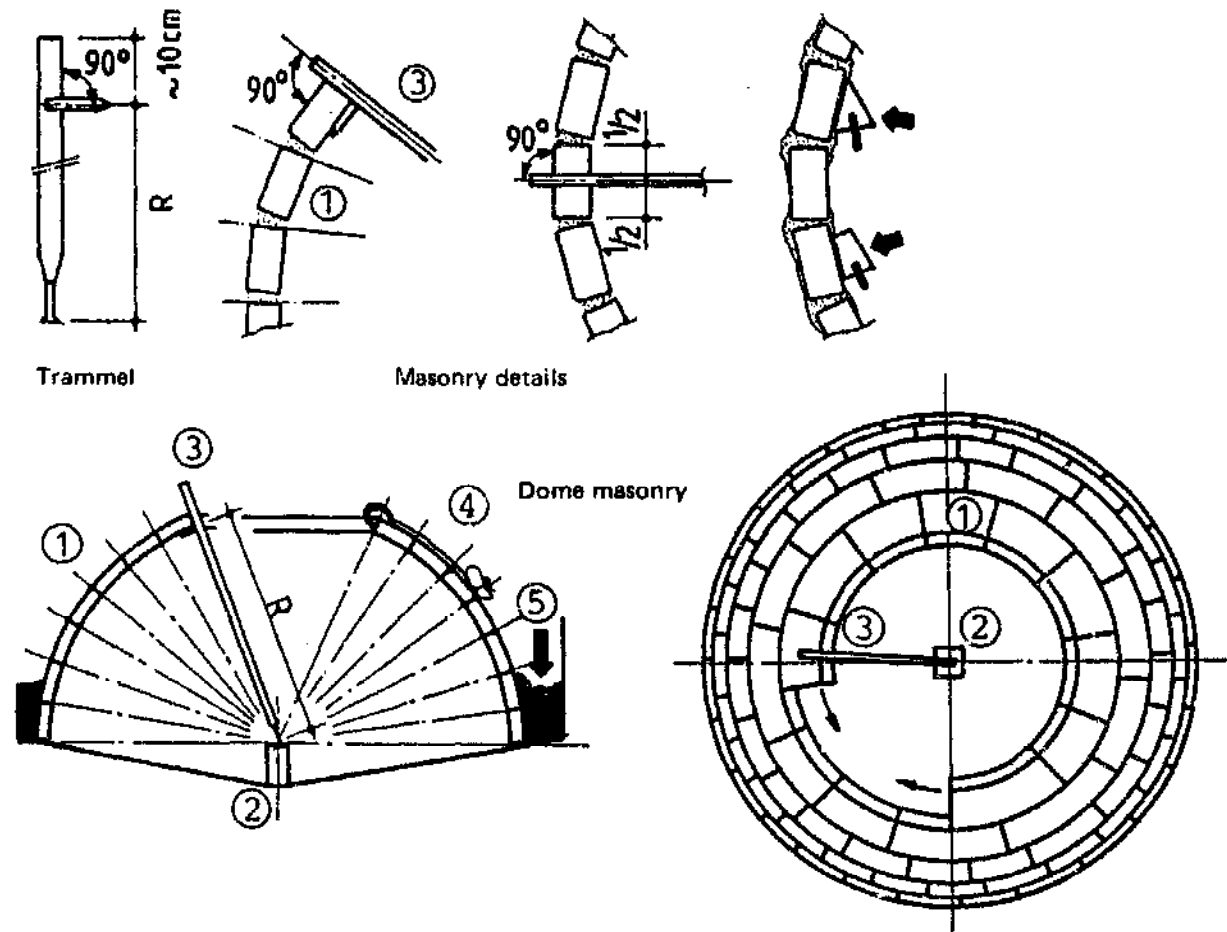
Dome masonry

— finding and fixing the centerpoint of the dome radius in relation to the level line

— layer-by-layer setting of the dome masonry, with the bricks set in mortar, positioned and aligned with the aid of the trammel and tapped for proper seating

— in the upper part of the dome — when the trammel is standing at a steeper angle than 45°, the bricks must be held in place until each course is complete. Sticks or clamps with counterweights can be used to immobilize them.

Each closed course is inherently stable and therefore need not be held in place any longer. The mortar should be sufficiently adhesive, i.e. it should be made of finely sieved sand mixed with an adequate amount of cement.

Table 5.9: Mortar mixing ratios (Source: Sasse, 1984)

Type of mortar	Cement		Lime		Sand
Masonry mortar	2	:	1	:	10
Masonry mortar	1		:		6
Rendering mortar	1		:		4 – 8

Rendering

Mortar consisting of a mixture of cement, sand and water is needed for joining the bricks and rendering the finished masonry. Biogas plants should be built with cement mortar, because lime mortar is not resistant to water.

The sand for the mortar must be finely sieved and free of dust, loam and organic material. That is, it must be washed clean.

Special attention must be given to the mortar composition and proper application for rendering, since the rendering is of decisive importance with regard to the biogas plant's durability and leaktightness. Ensure that:

— trowelling is done vigorously (to ensure compact rendering)

— all edges and corners are rounded off

— each rendering course measures between 1.0 and 1.5 cm

— the rendering is allowed to set/dry slowly (keep shaded and moist, as necessary)

— the material composition is suitable and mutually compatible

— a rated break ring is provided for a fixed-dome plant

Crack-free rendering requires lots of pertinent experience and compliance with the above points. Neither the rendering nor the masonry is gastight and therefore has to be provided with a seal coat around the gas space (cf. chapter 5.4.4).

Table 5.10: Suitability tests for rendering/mortar sands (Source: Sasse, 1984)

Test	Requirement
1. Visual check for coarse particles	Particle size: <7 mm
2. Determining the fines fraction by immersion in a glass of water: 1/2 l sand mixed with 1 l water and left to stand for 1 h, after which the layer of silty mud at the top is measured.	Silt fraction: <10%
3. Check for organic matter by immersion in an aqueous solution of caustic soda: 1/2 l sand in 1 l 3% caustic soda with occasional stirring. Notation of the water's color after 24 h.	*Clear-to-light-yellow* = low org. content: suitable for use *Reddish brown* = high org. content: unsuitable for use

5.4.4 Gasholder

Basically, there are three different designs/ types of construction for gasholders used in simple biogas plants:
- integrated floating drums
- fixed domes with displacement system and
- separate gasholders

Floating-drum gasholders

Most floating-drum gasholders are made of 2–4 mm-thick sheet steel, with the sides made somewhat thicker than the top in order to counter the higher degree of corrosive attack. Structural stability is provided by L-bar bracing that simultaneously serves to break up surface scum when the drum is rotated.

A guide frame stabilizes the gas drum and keeps it from tilting and rubbing on the masonry. The two equally suitable types used must frequently are:
- an internal rod & pipe guide with a fixed (concrete-embedded) cross pole (an advantageous configuration in connection with an internal gas outlet)
- external guide frame supported on three wooden or steel legs (cf. fig. 5.7).

For either design, it is necessary to note that substantial force can be necessary to turn the drum, especially if it is stuck in a heavy layer of floating scum. Any gasholder with a volume exceeding 5 or 6 m^3 should be equipped with a double guide (internal and external).

All grades of steel normally used for making gasholders are susceptible to moisture-induced rusting both inside and out. Conse-

Fig. 5.22: Construction of a metal gasholder with internal guide frame. 1 Lattice beam serving as cross pole, 2 Cross pole with bracing, 3 Gas pipe (2% gradient), 4 Guide frame, 5 Braces for shape retention and breaking up the scum layer, 6 Sheet steel (2–4 mm) serving as the drum shell (Source: OEKOTOP/Sasse, 1984)

Schematic diagram
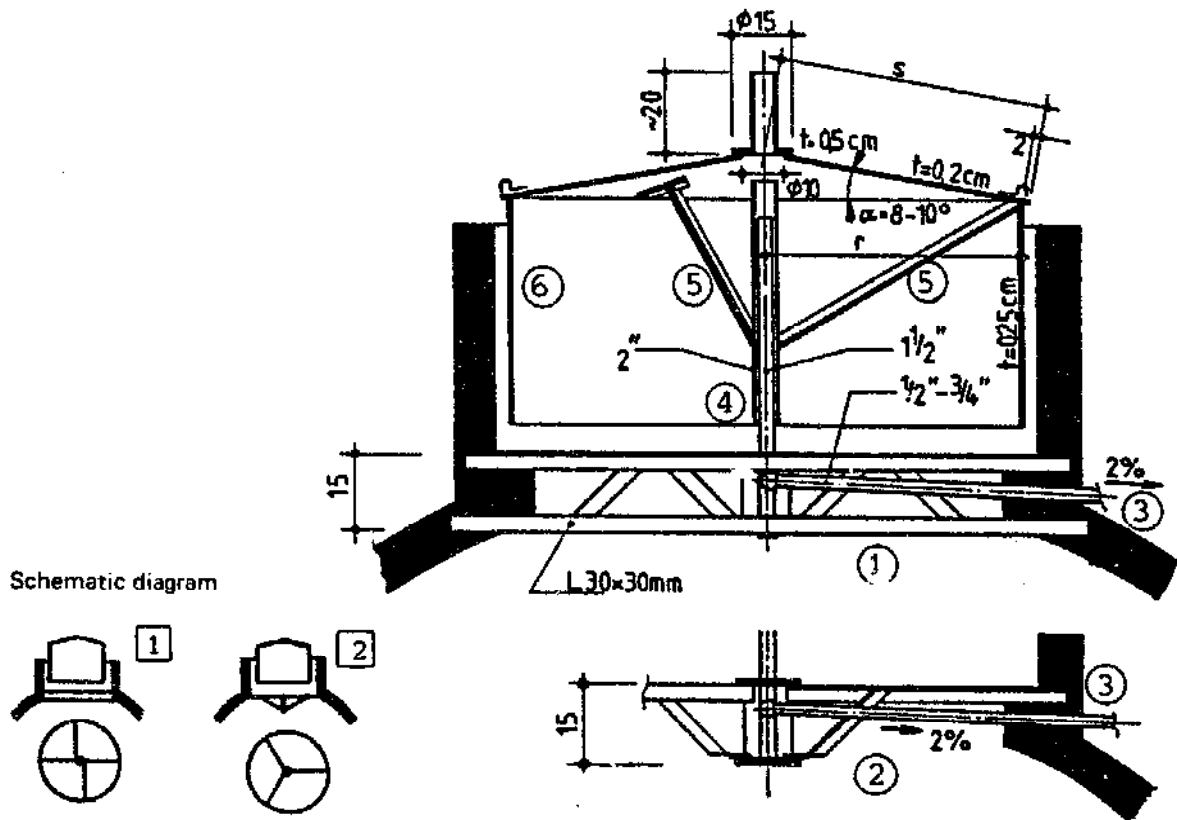
quently, a long service life requires proper surface protection consisting of:

- thorough derusting and desoiling
- primer coat of minium
- 2 or 3 cover coats of plastic/bituminous paint.

The cover coats should be reapplied annually. A well-kept metal gasholder can be expected to last between 3 and 5 years in humid, salty air or 8–12 years in a dry climate.

Materials regarded as suitable alternatives to standard grades of steel are galvanized sheet metal, plastics (glass-reinforced plastic/GRP, plastic sheeting) and ferrocement with a gastight lining. The gasholders of water-jacket plants have a longer average service life, particularly when a film of used oil is poured on the water seal to provide impregnation.

Fixed domes

In a fixed-dome plant the gas collecting in the upper part of the dome displaces a corresponding volume of digested slurry. The following aspects must be considered with regard to design and operation:

- An overflow must be provided to keep the plant from becoming overfilled.
- The gas outlet must be located about 10 cm higher than the overflow in order to keep the pipe from plugging up.
- A gas pressure of 1 mWG or more can develop in the gas space, Consequently, the plant must be covered with enough earth to provide an adequate counterpressure; special care must be taken to properly secure the entry hatch, which may require weighing it down with 100 kg or more.

The following structural measures are recommended for avoiding or at least limiting the occurrence of cracks in the dome (cf. fig. 5.23):

- For reasons of static stability, the centerpoint of the dome radius should be lowered by 0.25 R (corresponding to bottom center of the foundation). This changes the geometry of the digester, turning it into a spherical segment, i.e. flatter and wider, which can be of advantage for the plant as a whole.
- The foot of the dome should be made more stable and secure by letting the foundation slab project out enough to accept an outer ring of mortar.

Fig. 5.23: Construction of a fixed-dome gasholder. 1 Slurry level for an empty gasholder (zero line), 2 Slurry level for a full gasholder, 3 Overflow, 4 Inlet = overpressure relief, 5 Earth cover (at least 60 cm), 6 Reinforcing ring at foot of dome, 7 Max. gas pressure. A Detail: wall construction: .1 Outer rendering, .2 Masonry, .3 Twolayer inner rendering, .4 Seal coat. B Detail: rated break point: .1 Masonry bricks (laid at right angles), .2 Joint reinforced with chicken wire, .3 Seal rendering – inside and out (Source: OEKOTOP)
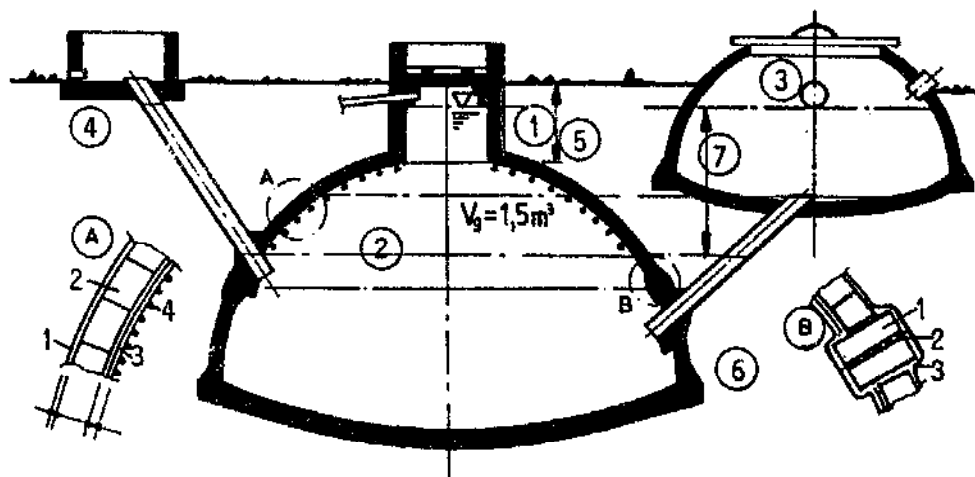
A With gas outlet in wedged-in cover
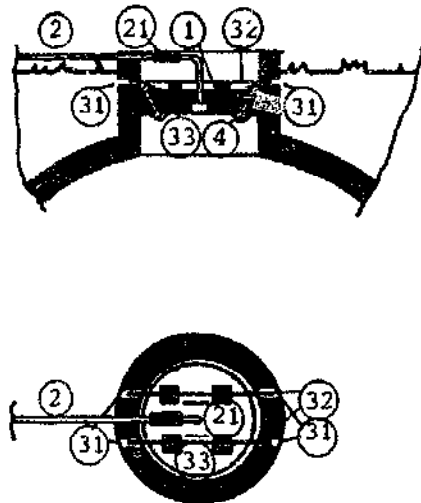
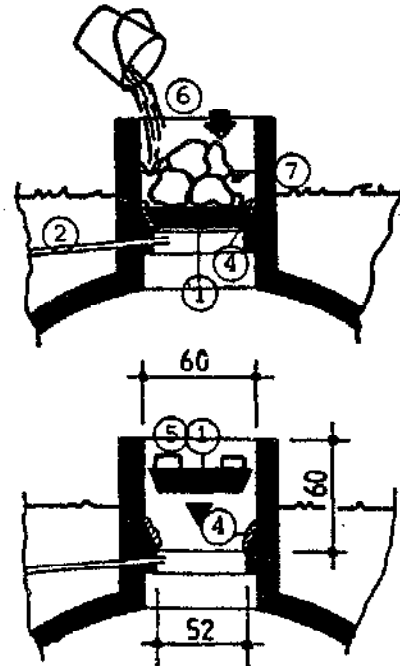B With lateral gas outlet below weighed-down cover

Fig. 5.24: Entry hatch of a fixed-dome biogas plant. 1 Concrete cover, 2 Gas pipe, 21 Flexible connection (hose), 3 Cover wedging, 31 Length of pipe anchored in the masonry, 32 Retaining rod, 33 Wooden/metal wedges, 4 Edge seal made of loam/mastic compound, 5 Handles, 6 Weights, 7 Water (Source: OEKOTOP)

— A rated break/pivot ring should be provided at a point located between 1/2 and 2/3 of the minimum slurry level. This in order to limit the occurrence or propagation of cracks in the vicinity of the dome foot and to displace forces through its stiffening/articulating effect such that tensile forces are reduced around the gas space.

In principle, however, masonry, mortar and concrete are not gastight, with or without mortar additives. Gastightness can only be achieved through good, careful workmanship and special-purpose coatings. The main precondition is that the masonry and rendering be strong and free of cracks. Cracked and sandy rendering must be removed. In most cases, a plant with cracked masonry must be torn down, because not even the best seal coating can render cracks permanently gastight.

Some tried and proven seal coats:

— multilayer bitumen, applied cold (hot application poses the danger of injury by burns and smoke nuisance); solvents cause dangerous/explosive vapors. Two to four thick coats required.

Table 5.11: Quality ratings for various dome-sealing materials (Source: OEKOTOP)

Material	Processing	Seal	Durability	Costs
Cold bitumen	++	o	o	++
Bitumen with alu-foil	+	++	+	+
Epoxy resin	++	+	++	—
Paraffin	+	o	o	++

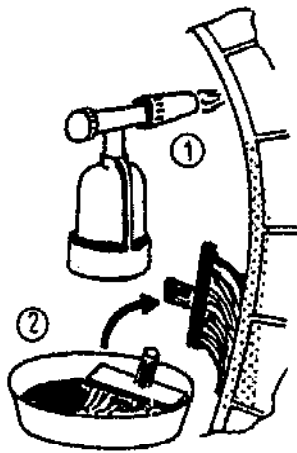++ very good   + good   o satisfactory   — problematic

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Fig. 5.25: Sealing the masonry with paraffin.
1 Heat wall to 60–80 °C with soldering torch,
2 Apply hot (100 °C) paraffin (Source: OEKOTOP/
BEP Tanzania)

Fig. 5.26: Separate, mobile, plastic-sheet gasholder.
1 Cart for gasholder volumes of 1 m³ and more,
2 Stabilizing weights and frame, 3 Reinforced-
plastic gasholder (Source: Wesenberg 1985)

– *bitumen with aluminum foil:* thin sheets of overlapping aluminum foil applied to the still-sticky bitumen, followed by the next coat of bitumen.

– *plastics,* as a rule epoxy resin or acrylic paint; very good but expensive.

– *paraffin,* diluted with 2–5% kerosene, heated to 100 °C and applied to the preheated masonry. The paraffin penetrates deep into the masonry, thus providing an effective (deep) seal. Use kerosene/gas torch to heat masonry.

In any case, a pressure test must be performed before the plant is put in service (cf. chapter 7.1).

Plastic gasholders

Gasholders made of plastic sheeting serve as integrated gasholders (cf. chapter 5.3.3: earth pits), as separate balloon/bag-type gasholders and as integrated gas-transport/storage elements.

For plastic (sheet) gasholders, the structural details are of less immediate interest than the question of which materials can be used. Table 5.12 (p. 74) surveys the relative suitability of various commercial grades of plastic sheeting.
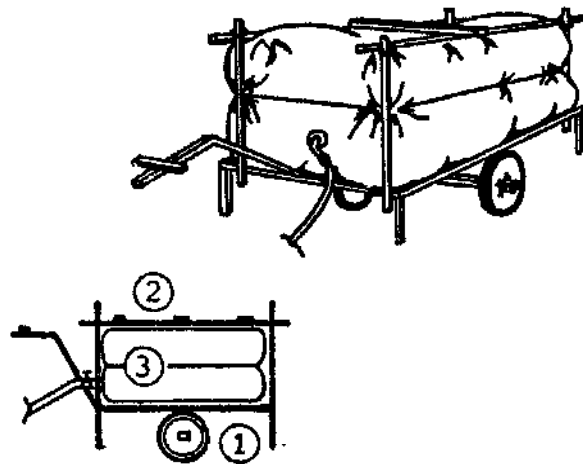
Separate gasholders

Differentiation is made between:

– low-pressure, wet and dry gasholders (10–50 mbar) Basically, these gasholders are identical to integrated and/or plastic (sheet) gasholders. Separate gasholders cost more and are only worthwhile in case of substantial distances (at least 50–100 m) or to allow repair of a leaky fixed-dome plant.

– medium- or high-pressure gasholders (8–10 bar/200 bar)

Neither system can be considered for use in small-scale biogas plants. Even for large-scale plants, they cannot be recommended under the conditions anticipated in most developing countries. High-pressure gas storage in steel cylinders (as fuel for vehicles) is presently under discussion. While that approach is possible in theory, it would be complicated and, except in a few special cases, prohibitively expensive. It would also require the establishment of stringent safety regulations.

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Table 5.12: Properties of plastic sheeting – gasholder suitability ratings (Source: UTEC 1985)

Description	Material	Spec. weight	Permissible internal pressure	Slit-tear resistance	Mechanical properties	Temperature stability	Weather resistance	Animal attack, rot/mold	Chemical stability	CH$_4$-permeability	Processing	Suitability as gasholder
	—	g/m²	mbar	N	—	°C	—	—	—	cm³ × mm / m² × d × at		
1	2	3	4	5	6	7	8	9	10	11	12	13
Solid sheeting per 1.0-mm thickness	PVC	1400	42	50	--	90/ 65	o	–/o	+	365/1300	HF, HW, HA HT, C	–
	PE	950	42	100	--	90/ 70	–/o	o	o	760/488	HF, HW, HA	–/o
	IIR	1300	9	32	+	170/110	++	+	o	290/230	HV, FF, C	+
	EPDM	1200	4	32	+	170/120	++	+	o	3200	HV, FF, C	+
Laminated synthetic fabrics of various thickness	PVC	750/ 1400	59– 80	240– 300	++	90/65	o	–/o	+	310/–	HF, HW, HA, HT, C	+
	CPE	1100			–	70	+	+	+	165/200	HF, HW, HA	–
	CSM	1100			++	140/90	++	+	o	290/370	HV, C	+
	CR	1100			++	90	++	+	o	1010/720	HV, C	++

2   PVC (polyvinyl chloride)
    PE (polyethylene)
    CPE (chlorinated polyethylene)
    IIR (isobutylene-isoprene rubber)
    EPDM (ethylene-propylene diene monomer)
4   Inflatable gasholder, approx. 2.5 m³,
    3-fold protection against rupture
6/8/9 – poor, o satisfactory,
10/13 + good, ++ very good

7   Short-term/continuous load
11   Permeability coefficient, P, for new material
12   HF = high-frequency seam welding
    HW = hot-wedge seam welding
    HA = hot-air seam welding
    C   = cementing
    HV = hot vulcanizing
    FF = fusion firing
    HT = heat-solvent tape sealing

5.4.5 Gas pipe, valves and fittings

Gas pipe

The following types of gas pipes are in use:
— PVC pipes with adhesive joints
— steel pipes (water supply pipes) with screw couplings
— plastic hoses.

Galvanized steel water supply pipes are used most frequently, because the entire piping system (gas pipe, valves and fittings) can be made of universally applicable English/U.S. Customary system components, i.e. with all dimensions in inches. Pipes with nominal dimensions of 1/2″ or 3/4″ are adequate for small-to-midsize plants of simple design and pipe lengths of less than 30 m. For larger

Table 5.13: Gas-pipe pressure losses (Source: OEKOTOP)

Volum. flow, Q (m³/h)	Pipe (galv. steel pipe)					
	1/2"		3/4"		1"	
	v^1 m/s	dp/l^2 cm WG/10 m	v^1 m/s	dp/l^2 cm WG/10 m	v^1 m/s	dp/l^2 cm WG/10 m
0.1	0.35	0.03	0.16	0.004	0.09	0.001
0.2	0.71	0.12	0.32	0.02	0.18	0.004
0.4	1.4	0.47	0.64	0.06	0.36	0.016
0.6	2.1	1.06	0.94	0.15	0.53	0.034
0.8	2.8	1.9	1.3	0.27	0.72	0.06
1.0	3.5	2.9	1.6	0.41	0.88	0.09
1.5	5.3	6.7	2.3	0.85	1.33	0.2
2.0	7.0	11.8	3.2	1.6	1.8	0.4

[1] Velocity of flow in the pipe
[2] Differential pressure (pipe only) stated in cm WG per 10 m pipe

plants, longer gas pipes or low system pressure, a detailed pressure-loss (pipe-sizing) calculation must be performed (cf. chapter 10.2).

When installing a gas pipe, special attention must be paid to:
— gastight, friction-type joints
— line drainage, i.e. with a water trap at the lowest point of the sloping pipe in order to rule out water pockets
— protection against mechanical impact.
Some 60% of all system outages are attributable to defective gas pipes. For the sake of standardization, it is advisable to select a single size for all pipes, valves and fittings.

Valves and fittings

To the extent possible, ball valves or cock valves suitable for gas installations should be used as shutoff and isolating elements. Gate valves of the type normally used for water pipes are conditionally suitable. Any water valves used must first be checked for gas-tightness.

Gas manometer

A U-tube pressure gauge is quick and easy to make and can normally be expected to meet the requirements also of a fixed-dome system.

Fig. 5.27: Gas pipe, valves and fittings of a biogas plant. 1 Plant shutoff valve, 2 Water trap, 3 Pressure gauge, 4 House shutoff valve, 5 Cookstove, 6 Lamp, 7 Appliance shutoff valve, 8 Gasmeter (Source: OEKOTOP)
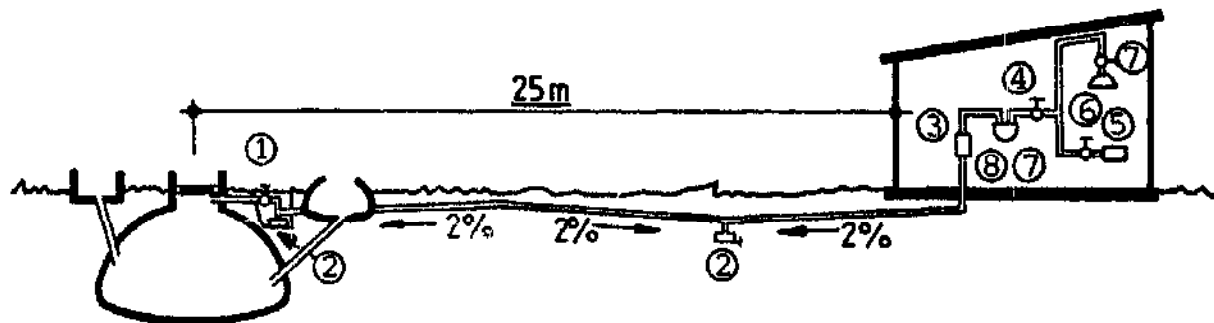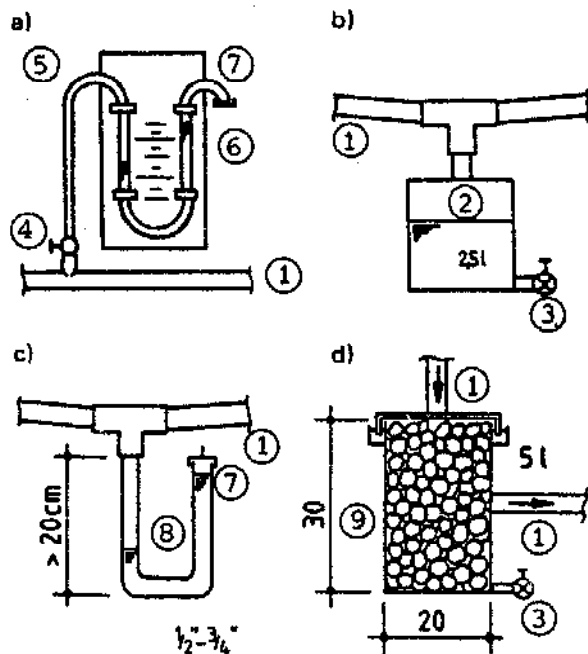
Fig. 5.28: Gas valves and fittings: U-tube pressure gauge (a), water trap with drain valve (b), U-tube water separator (c), "gravel-pot" flashback arrestor (d). 1 Gas pipe, 2 Condensate collector, 3 Shutoff valve, 4 Manometer valve, 5 U-tube pressure gauge made of transparent hose, 6 Wooden balls, 7 Anti-evaporation cap, 8 U-tube, 9 "Gravel-pot" flashback arrestor (approx. 5 l) filled with 20 mm gravel (Source: OEKOTOP)

Pressure relief

The task of running a fixed-dome system can be made easier by installing a spring-loaded pressure reducing valve that guarantees a constant (adjustable) supply pressure.

Water separation

If at all possible, the water trap should operate automatically. However since fixed-dome systems need a high water seal, often amounting to more than 1 m WG, the use of condensate collector with a manually operated drain valve is advisable.

Backflow prevention

As a rule, the water trap also functions as a flashback chamber. If deemed necessary, a gravel trap can be installed for added safety.

5.5 Biogas Utilization

5.5.1 Composition and properties of biogas

Biogas is a mixture of gases that is composed chiefly of:

— methane, CH_4	40–70 vol. %
— carbon dioxide, CO_2	30–60 vol. %
— other gases	1–5 vol. %, including
— hydrogen H_2	0–1 vol. %
— hydrogen sulfide, H_2S	0–3 vol. %

Like those of any gas, the characteristic values of biogas are pressure and temperature-dependent. They are also affected by water vapor. The factors of main interest are:

— volumetric change as a function of temperature and pressure,
— change in calorific value as a function of temperature, pressure and water-vapor content, and
— change in water-vapor content as a function of temperature and pressure.

Chapter 10.2 contains pertinent tables, formulae and nomograms for use in calculating conditions of state.

5.5.2 Conditioning of biogas

While the biogas produced by the plant can normally be used as it is, i.e. without further treatment/conditioning, various conditioning processes are described in this chapter to cover possible eventualities.

Reducing the moisture content of the biogas, which is usually fully saturated with water vapor. This involves cooling the gas, e.g. by routing it through an underground pipe, so that the excess water vapor condenses out at the lower temperature. When the gas warms up again, its relative vapor

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Table 5.14: Composition and properties of biogas and its constituents under s.t.p. conditions (0 °C, 1013 mbar) (Source: OEKOTOP, compiled from various sources)

Constituents and properties	CH_4	CO_2	H_2	H_2S	60% CH_4/ 40% CO_2	65% CH_4/ 34% CO_2/ 1% rest
Volume fraction (%)	55–70	27–44	1	3	100	100
Net calorific value (kWh/m³)	9.9	–	3.0	6.3	6.0	6.8
Ignition threshold (% in air)	5–15	–	4–80	4–45	6–12	7.7–23
Ignition temperature (°C)	650–750	–	585	–	650–750	650–750
Crit. pressure (bar)	47	75	13	89	75–89	75–89
Crit. temp. (°C)	–82.5	31.0	–240	100.0	–82.5	–82.5
Normal density (g/l)	0.72	1.98	0.09	1.54	1.2	1.15
Gas/air-density ratio	0.55	2.5	0.07	1.2	0.83	0.91
Wobbe index, K (kWh/m³)	13.4	–	–	–	6.59	7.15
Spec. heat, cp (kJ/m³ · °C)	1.6	1.6	1.3	1.4	1.6	1.6
Flame propagation (cm/s)	43	–	47	–	36	38

content decreases (cf. chapter 10.2 for calculations).

The "drying" of biogas is especially useful in connection with the use of dry gas meters, which otherwise would eventually fill up with condensed water.

Reduction of the hydrogen-sulfide content (H_2S) may be necessary if the biogas is found to contain an excessive amount, i.e. more than 2%, and is to be used for fueling an engine. Since, however, most biogas contains less than 1% H_2S, desulfurization is normally unnecessary, especially if it is to be used for operating a stationary engine.

For small-to-midsize systems, desulfurization can be effected by absorption onto ferric hydrate (Fe (OH)$_3$), also referred to as bog iron, a porous form of limonite. The porous, granular purifying mass can be regenerated by exposure to air.

The absorptive capacity of the purifying mass depends on its iron-hydrate content: bog iron containing 5–10% Fe(OH)$_3$ can absorb about 15 g sulfur per kg without being regenerated and approximately 150 g/ kg through repetitive regeneration. It is a very noteworthy fact that many types of tropical soil (laterites) are naturally ferr-

iferous and, hence, suitable for use as purifying mass.

Reduction of the carbon-dioxide content (CO_2) is very complicated and expensive. In principle, CO_2 can be removed by ab-

Fig. 5.29: Ferric-hydrate gas purifier. 1 Gas pipe, 11 Raw-gas feed pipe, 12 Clean-gas discharge pipe, 13 Purging line, 2 Metal gas purifier, 3 Shelves for purifying mass, 4 Purifying mass (Source: Muche 1984)
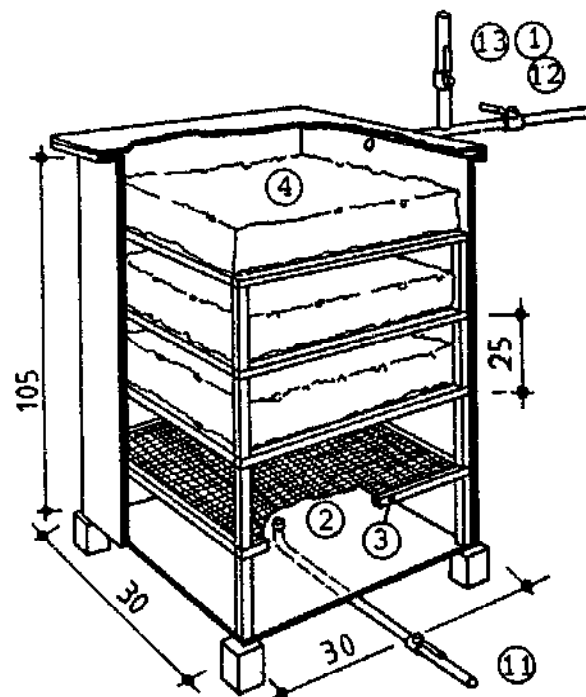
sorption onto lime milk, but that practice produces "seas" of lime paste and must therefore be ruled out, particularly in connection with large-scale plants, for which only high-tech processes like microscreening are worthy of consideration. CO_2 "scrubbing" is rarely advisable, except in order to increase the individual bottling capacity for high-pressure storage.

5.5.3 Biogas appliances

Biogas is a lean gas that can, in principle, be used like any other fuel gas for household and industrial purposes, the main prerequisite being the availability of specially designed biogas burners or modified consumer appliances. The relatively large differences in gas quality from different plants, and even from one and the same plant (gas pressure, temperature, calorific value, etc.) must be given due consideration.

The heart of any gas appliance is the burner. In most cases, atmospheric-type burners operating on premixed air/gas fuel are considered preferable.

Due to complex conditions of flow and reaction kinetics, gas burners defy precise calculation, so that the final design and adjustments must be arrived at experimentally.

Accordingly, the modification and adaptation of commercial-type burners is an ex-

Table 5.15: Pointers on flame adjustment (Source: OEKOTOP)

Problem	Cause – Remedy
elongated, yellowish flame	lack of combustion air – open the air supply
flame "lifts off"	excessive exit velocity – use smaller injector, reduce the gas pressure, reduce the air supply
flame "flashes back"	exit velocity too low – use larger injector, increase the gas pressure, open the air supply, reduce the size of the burner jets
flame "too small"; not enough fuel	fuel shortage – use larger injector, increase the gas pressure
flame "too big"; excessive fuel supply/consumption	excessive fuel supply – reduce the gas pressure, use smaller injector

perimental matter. With regard to butane and propane burners, i.e. the most readily available types, the following pointers are offered:

– Butane/propane gas has up to 3 times the calorific value of biogas and almost twice its flame-propagation rate.

– Conversion to biogas always results in lower performance values.

Practical modification measures include:

– expanding the injector cross section by a factor of 2–4 in order to increase the flow of gas

Fig. 5.30: Schematic drawing of a biogas burner and its parts. 1 Gas pipe, 2 Gas-flow shutoff/reducing valve, 3 Jets (ϕ = 1–2 mm), 4 Mixing chamber for gas and combustion air, 5 Combustion air intake control, 6 Burner head, 7 Injector (Source: Sasse 1984)
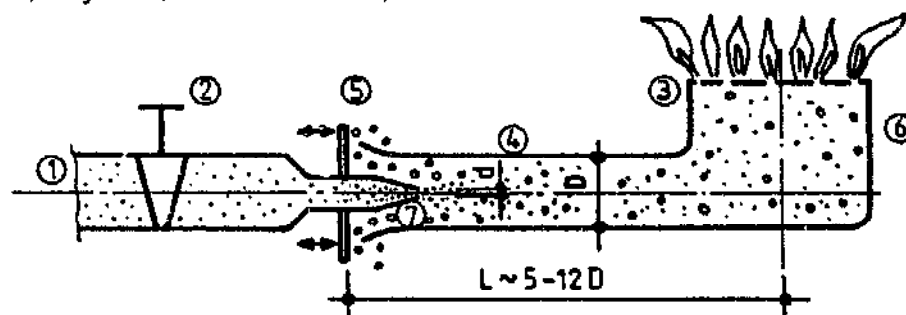
Table 5.16: Comparison of various internationally marketed biogas burners (Source: OEKOTOP, compiled from various sources)

Type of burner[1]	Number of flames	Gas consumption	Burning properties	Handling
Peking No. 4/PR China (3)	1	200 l/h	+	o
Jackwal/Brazil (1)	2	2 × 150 l/h	++	+
Patel GC 32/India	2	2 × 250 l/h	o	++
Patel GC 8/India	1	230 l/h	+	++
KIE burner/Kenya (2)	2	?	+	++

++ very good   + good   o average
[1] Number of burner shown in figure 5.31

— modifying the combustion-air supply, particularly if a combustion-air controller is provided
— increasing the size of the jet openings (avoid if possible)
The aim of all such measures is to obtain a stable, compact, slightly bluish flame.

Gas cookers/stoves

Biogas cookers and stoves must meet various basic requirements:
— simple and easy operation
— versatility, e.g. for pots of various size, for cooking and broiling
— easy to clean
— acceptable cost and easy repair
— good burning properties, i.e. stable flame, high efficiency
— attractive appearance
A cooker is more than just a burner. It must satisfy certain aesthetic and utility require-

ments, which can vary widely from region to region. Thus, there is no such thing as an all-round biogas burner.
Field data shows that 2-flame stable burners are the most popular type (cf. fig. 5.31).

Table 5.17: Biogas consumption for cooking (Source: OEKOTOP, compiled from various sources)

To be cooked:	Gas consumption	Time
1 l water	30–40 l	8–12 min
5 l water	110–140 l	30–40 min
3 l broth	~60 l/h	
1/2 kg rice	120–140 l	~40 min
1/2 kg legumes	160–190 l	~60 min
1 tortilla (fried)	10–20 l	~ 3 min

Gas consumption per person and meal	150–300 l/d
Gas consumption per 5-member family (2 cooked meals)	1500–2400 l/d

Fig. 5.31: Various types of biogas burners. 1 2-flame lightweight burner (2 × 150 l/h), 2 2-flame stable burner (2 × 250 l/h), 3 1-flame burner (200 l/h) (Source: OEKOTOP)
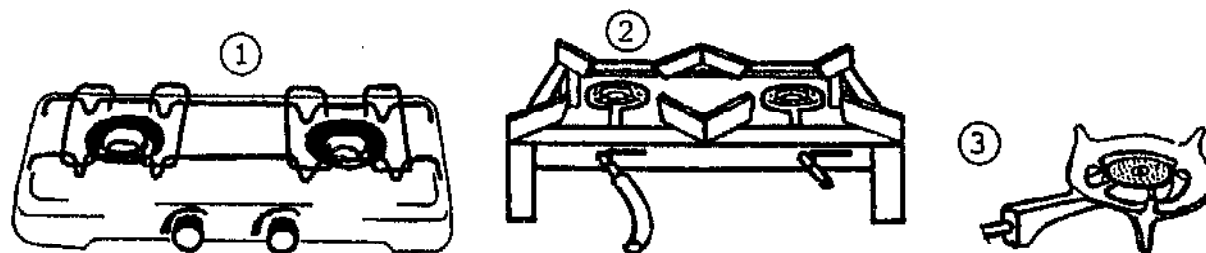
Photo 18: Cooking with biogas on a converted cookstove in Nicaragua (Source: BEP Nicaragua)

Photo 19: Lighting an Indian-type biogas lamp (Source: BEP Burkina Faso)

Photo 20: A two-flame lightweight cooker (Source: OEKOTOP)

Photo 21: A single-flame KIE-burner made in Kenya (Source: OEKOTOP, BEP Tanzania)

Single-flame burners and lightweight cook-stoves tend to be regarded as stop-gap solutions for want of suitable alternatives.

Biogas cookers require purposive installation with adequate protection from the wind. Before any cooker is used, the burner must be carefully adjusted, i.e.:

 — for a compact, bluish flame,
 — the pot should be cupped by the outer cone of the flame without being touched by the inner cone,
 — the flame should be self-stabilizing, i.e. flameless zones must re-ignite automatically within 2 to 3 seconds.

Test measurements should be performed to optimize the burner setting and minimize consumption. The physical efficiency of a typical gas burner ranges from 0.6 to 0.8.

Table 5.18: Tests for biogas cookers/stoves (Source: OEKOTOP)

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1. Measuring the efficiency with water

$$\eta = \frac{QW \cdot (T1 - T2) \cdot cW + EW \cdot L}{n.c.v. \cdot Q}$$

η = burner efficiency (–)
QW = quantity of heated water (kg)
T1,T2 = initial and final temperature ($^\circ$C)
cW = spec. heat capacity = 4.2 kJ/kg
EW = quantity of evaporated water (kg)
L = evaporation heat loss = 2260 kJ/kg
n.c.v. = net cal. value of biogas (kJ/m^3)
Q = quantity of biogas (m^3)

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2. Gas consumption for holding the temperature at boiling point (simmering temperature –95 $^\circ$C), i.e. the amount of gas needed per unit of time to maintain a water temperature of 95 $^\circ$C

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3. Standard cooking test
This test determines how much gas is needed to cook a standard meal, e.g. 500 g rice and 1000 g water; the standard meal is specified according to the regional staple diet

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4. Complete-meal tests
Everything belonging to a complete meal is cooked by a native erson.

Biogas lamps

The bright light given off by a biogas lamp is the result of incandescence, i.e. the intense heat-induced luminosity of special metals, so-called "rare earths" like thorium, cerium, lanthanum, etc. at temperature of 1000–2000 $^\circ$C.

At 400–500 lm, the maximum light-flux values that can be achieved with biogas lamps are comparable to those of a normal 25–75 W light bulb. Their luminous efficiency ranges from 1.2 to 2 lm/W. By comparison, the overall efficiency of a light bulb comes to 3–5 lm/W, and that of a fluorescent lamp ranges from 10 to 15 lm/W.

The performance of a biogas lamp is dependent on optimal tuning of the incandescent body (gas mantle) and the shape of the flame at the nozzle, i.e. the incandescent body must be surrounded by the inner (= hottest) core of the flame at the minimum gas consumption rate. If the incandescent body is too large, it will show dark spots; if the flame is too large, gas consumption will be too high for the light-flux yield. The lampshade reflects the light downward, and the glass prevents the overly rapid loss of heat.

Fig. 5.32: Schematic drawing of a biogas lamp. 1 Gas pipe, 21 Shutoff valve, 22 Adjusting valve, 3 Primary air supply (adjustable), 4 Mixing chamber, 5 Incandescent body – gas mantle, 6 Porcelain head, 7 Disk reflector, 8 Glass (Source: OEKOTOP/ Jackwal)
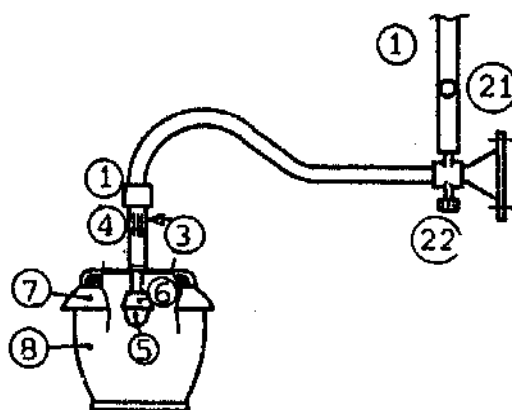
Table 5.19: Standard lighting terms and units of measure (Source: OEKOTOP)

Term/definition	Unit, formula
Luminous flux (F) The light output defined as the luminous flux of a black body at 2042 °K per cm²	F, measured in lm (lumen)
Luminous intensity (I) The solid-angle light power $I = \dfrac{\text{luminous flux}}{\text{solid angle (w)}}$	I, measured in cd (candela) $I = F/w$ (cd = lm/w) half-space $w = 2\pi = 6.28$
Illuminance (E) light power per unit area $E = \dfrac{\text{luminous flux}}{\text{area (A)}}$	E, measured in lux (lx) $E = F/A$ (lx = lm/m²)
Spec. illuminance (Es) Effective incident illuminance, as measured normal to the light source at a defined distance from the source, referred to the input	$Es = \dfrac{E \times r^2}{V \times n.c.v.} \quad \left(\dfrac{lx \cdot m^2}{kW}\right)$ E = meas. illuminance r = distance between the incandescent body and the photoelectric cell V = biogas consumption n.c.v. = net calorific value
Luminous efficiency (Re) light power referred to the energy input (Ei)	$Re = F/Ei$ (lm/kW)

Sample calculation

Measured values:	Results:
Illuminance	Luminous intensity
E = 90 lx	$I = E \times r^2 = 90$ cd
meas. distance, r = 1.0 m	luminous flux
gas consumption, V = 110 l/h	$F = I \times w = 90 \times 6.28 = 565$ lm
cal. value, n.c.v. = 6 kWh/m³	luminous efficiency Re = F:Q = 565:110 = 5.1 lm/lxh Re = F/Ei = 565:660 = 0.9 lm/W

Practical experience shows that commercial-type biogas lamps are not optimally designed for the specific conditions of biogas combustion (fluctuating or low pressure, varying gas composition). The most frequently observed shortcomings are:

— excessively large nozzle cross sections
— excessively large gas mantles
— no possibility of changing the injector

— poor or lacking means of combustion-air control.

Such drawbacks result in unnecessarily high gas consumption and poor lighting. While the expert/extension officer has practically no influence on how a given lamp is designed, he can at least give due consideration to the aforementioned aspects when it comes to selecting a particular model.

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Table 5.20: Comparison of various biogas lamps (Source: Biogas Extension Program)

Type of lamp	Suitability[1]	Gas consumption
D 80 – 3 Juojiang/PR China	o [2]	?
Avandela – Jackwal/Brazil	+	100 l/h
Patel Outdoor-single/India	++	150 l/h
Camping-Gas	+	?

[1] Quality criteria: gas consumption, brightness, control
[2] Quality ratings: ++ very good, + good, o average

Biogas lamps are controlled by adjusting the supply of gas and primary air. The aim is to make the gas mantle burn with uniform brightness and a steady, sputtering murmer (sound of burning, flowing biogas). To check the criteria, place the glass on the lamp and wait 2–5 minutes, until the lamp has reached its normal operating temperature. The lamps compared in table 5.20 operate at a gas pressure of 5–15 cmWG. If the pressure is any lower, the mantle will not glow, and if the pressure is too high (fixed-dome systems) the mantle may tear.

Adjusting a biogas lamp requires two consecutive steps:

1. precontrol of the supply of biogas and primary air without the mantle, initially resulting in an elongated flame with a long inner core;
2. fine adjustment with the incandescent body in place, resulting in a brightly glowing incandescent body, coupled with slight further adjustment of the air supply (usually more).

The adjustment is at its best when the dark portions of the incandescent body have just disappeared. A luxmeter can be used for objective control of the lamp adjustment.

Radiant heaters

Infrared heaters are used in agriculture for achieving the temperatures required for raising young stock, e.g. piglets and chicks, in a limited amount of space. The nursery temperature for piglets begins at 30–35 °C for the first week and than gradually drops off to an ambient temperature of 18–23 °C in the 4th/5th week. As a rule, temperature control consists of raising or lowering the heater. Good ventilation is important in the stable/nursery in order to avoid excessive concentrations of CO or CO_2. Consequently, the animals must be kept under regular supervision, and the temperature must be checked at regular intervals.

Radiant heaters develop their infrared thermal radiation via a ceramic body that is heated to 600–800 °C (red-hot) by the biogas flame.

The heating capacity of the radiant heater is defined by multiplying the gas flow by its net calorific value ($E = Q \times n.v.c.$), since 95%

Fig. 5.33: Schematic drawing of a radiant heater. 1 Gas pipe, 2 Shutoff valve, 3 Safety pilot, 31 Heat sensor, 4 Mixing chamber, 5 Air supply, 6 Injector, 7 Ceramic panel with protective screen, 8 Reflector, 9 Hanger (Source: OEKOTOP / SBM)
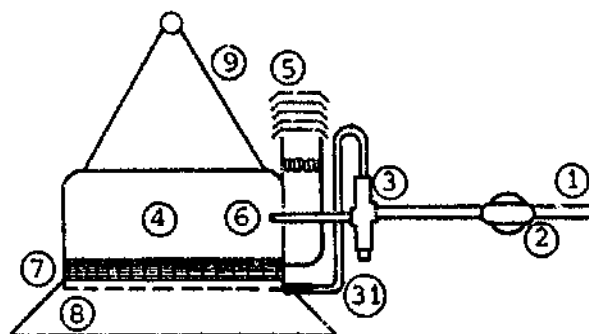
of the biogas' energy content is converted to heat. Small-heater outputs range from 1.5 to 10 kW thermal power.

Commercial-type heaters are designed for operating on butane, propane and natural gas at a supply pressure of between 30 and 80 mbar. Since the primary air supply is factory-set, converting a heater for biogas fueling normally consists of replacing the injector; experience shows that biogas heaters rarely work satisfactorily because the biogas has a low net calorific value and the gas supply pressure is below 20 mbar, in which case the ceramic panel is not adequately heated, i.e. the flame does not reach the entire surface, and the heater is very susceptible to draft.

Biogas-fueled radiant heaters should always be equipped with a safety pilot, and an air filter is required for sustained operation in dusty barns.

Incubators

Incubators are supposed to imitate and maintain optimal conditions for hatching eggs. They are used to increase brooding efficiency.

Indirectly warm-water-heated planar-type incubators in which a biogas burner heats

front view
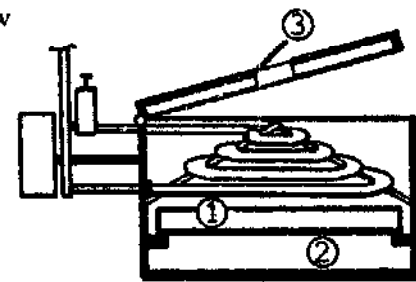
plan view
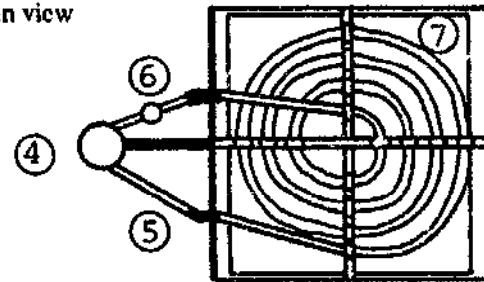
detail
heating element
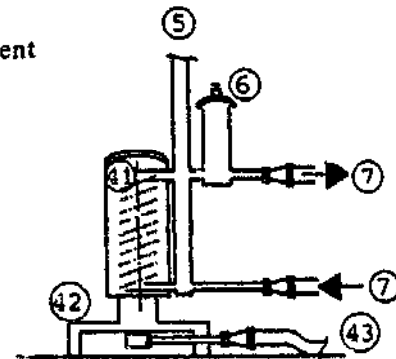
Fig. 5.34: Schematic drawing of an incubator. 1 Incubating chamber, 2 Removable tray, 3 Cover/venting lid, 4 Heating element, 41 Heating coil, 42 Burner, 43 Gas pipe, 5 Water filler neck and expansion tank, 6 Vent valve, 7 Warming element (plastic hose). Biogas consumption rate: 30-50 l/h (Source: Wesenberg 1985)

Table 5.21: Artificial brooding requirements, exemplified for a chick incubator (Source: Wesenberg 1985)

Incubation heat	37.8 °C at the beginning, declining to 30.0 °C at the end of the incubation period. The temperature should be kept as constant as possible. Any temperature in excess of 39 °C can damage the eggs.
Hatching time:	approximately 21 days
Relative humidity:	60–90 %
Ventilation:	A steady supply of fresh air (but not draft) is required to keep the CO_2 content below 0.8 %.
Turning the eggs:	Incubating eggs must be turned as often as 8 times a day to keep the chicks from sticking to the inside of the shell.
Barren eggs:	Unfertilized eggs and eggs containing dead chicks must be removed (danger of infection). The eggs should be candletested once per week to ensure timely detection.

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Table 5.22: Technical data of absorption refrigerators (Source: OEKOTOP)

Heating medium	gas, kerosene, electricity
Max. ambient temperature	40 °C
Heating temperature	100–150 °C
Cooling temperature	
– refrigerator	5–10 °C
– freezer	down to approx. –12 °C
Efficiency	1.5 – 4.0% of the thermal input
Gas consumption	a) calculable via the desired refrigeration capacity
	b) conversion of factory data via power input
Energy-consumption indices	1–4 W/l useful volume
	0.3–0.8 l.biogas/l useful volume X h

water in a heating element for circulation through the incubating chamber are suitable for operating on biogas. The temperature is controlled by ether-cell-regulated vents (cf. fig. 5.34).

Refrigerators

Absorption-type refrigerating machines operating on ammonia and water and equipped for automatic thermosiphon circulation can be fueled with biogas.

Since biogas is only the refrigerator's external source of heat, just the burner itself has to be modified. Whenever a refrigerator is converted for operating on biogas, care must be taken to ensure that all safety features (safety pilot) function properly; remote ignition via a piezoelectric element substantially increases the ease of operation.

5.5.4 Biogas-fueled engines

Basic considerations

The following types of engines are, in principle, well-suited for operating on biogas:

— *Four-stroke diesel engines:*
A diesel engine draws in air and compresses it at a ratio of 17 : 1 under a pressure of

approximately 30–40 bar and a temperature of about 700 °C. The injected fuel charge ignites itself. Power output is controlled by varying the injected amount of fuel, i.e. the air intake remains constant (so-called mixture control).

— *Four-stroke spark-ignition engines*
A spark-ignition engine (gasoline engine) draws in a mixture of fuel (gasoline or gas) and the required amount of combustion air. The charge is ignited by a spark plug at a comparably low compression ratio of between 8 : 1 and 12 : 1. Power control is effected by varying the mixture intake via a throttle (so-called charge control).

Four-stroke diesel and spark-ignition engines are available in standard versions with power ratings ranging from 1 kW to more than 100 kW. Less suitable for biogas fueling are:

— loop-scavenging 2-stroke engines in which lubrication is achieved by adding oil to the liquid fuel, and

— large, slow-running (less than 1000 r.p.m.) engines that are not built in large series, since they are accordingly expensive and require complicated control equipment.

Biogas engines are generally suitable for powering vehicles like tractors and light-duty trucks (pickups, vans). The fuel is contained in 200-bar steel cylinders (e.g. welding-gas

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cylinders). The technical, safety, instrumentational and energetic cost of gas compression, storage and filling is substantial enough to hinder large-scale application. Consequently, only stationary engines are discussed below.

Essential terms and definitions

Knowledge of the following terms pertaining to internal combustion engines is requisite to understanding the context:

Piston displacement is the volume (cm^3, l) displaced by a piston in a cylinder in a single stroke, i.e. between the bottom and top dead-center positions (BDC and TDC, respectively). The total cylinder capacity (Vtot) comprises the swept volume (Vs) and the compression volume (Vc), i.e. Vtot = Vs + Vc.

The *compression ratio* (E) is the ratio of the maximum to the minimum volume of the space enclosed by the piston, i.e. prior to compression (Vtot) as compared to the end of the compression stroke (Vc). The compression ratio can be used to calculate the pressure and temperature of the compressed fuel mixture (E = Vtot/Vc).

The *efficiency* (η = Pc/Pf) is the ratio between the power applied to the crankshaft (Pc) and the amount of energy introduced with the fuel (Pf = V × n.c.v.).

Ignition and combustion: The firing point (diesel: flash point; spark-ignition engine: ignition point) is timed to ensure that the peak pressure is reached just after the piston passes top dead center (approx. $10°-15°$ crankshaft angle). Any deviation from the optimal flash/ignition point leads to a loss of power and efficiency; in extreme cases, the engine may even suffer damage. The flash/ignition point is chosen on the basis of

the time history of combustion, i.e. the rate of combustion, and depends on the compression pressure, type of fuel, combustion-air/ fuel ratio and the engine speed. The ignition timing (combustion) must be such that the air/fuel mixture is fully combusted at the end of the combustion cycle, i.e. when the exhaust valve opens, since part of the fuel's energy content would otherwise be wasted.

Air/Fuel-ratio and control: Proper combustion requires a fuel-dependent stoichiometric air/fuel-ratio (af-ratio). As a rule, the quality of combustion is maximized by increasing the air fraction, as expressed by the air-ratio coefficient (d = actual air volume/stoichiometric air volume).

For gasoline and gas-fueled engines, the optimal air/fuel ratio is situated somewhere within the range d = 0.8–1.3, with maximum power output at 0.9 and maximum efficiency (and clean exhaust) at 1.1. The power output is controlled by varying the mixture intake and, hence, the cylinder's volumetric efficient and final pressure, via the throttle. Diesel engines require an air-ratio of d = 1.3 at full load and 4–6 at low load, i.e. fuel intake is reduced, while the air intake remains constant.

Converting diesel engines

Diesel engines are designed for continuous operation (10 000 or more operating hours). Basically, they are well-suited for conversion to biogas according to either of two methods:

The dual-fuel approach
Except for the addition of a gas/air mixing chamber on the intake manifold (if need be, the air filter can be used as a mixing chamber), the diesel engine remains extensively unmodified. The injected diesel fuel still ignites itself, while the amount injected is

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automatically reduced by the speed governor, depending on how much biogas is introduced into the mixing chamber. The biogas supply is controlled by hand. The maximum biogas intake must be kept below the point at which the engine would begin to stutter. If that happens, the governor is getting too much biogas and has therefore turned down the diesel intake so far that ignition is no longer steady. Normally, 15–20% diesel is sufficiency, meaning that as much as 80% of the diesel fuel can be replaced by biogas. Any lower share of biogas can also be used, of course, since the governer automatically compensates with more diesel.

As a rule, dual-fuel diesels perform just as well as a comparable engine operating on pure diesel.

As in normal diesel operation, the speed is controlled by an accelerator lever, and load control is normally effected by hand, i.e. by adjusting the biogas valve (keeping in mind the maximum acceptable biogas intake level). In case of frequent power changes joined with steady speed, the biogas fraction should be reduced somewhat to let the governer decrease the diesel intake without transgressing the minimum amount. Thus, the speed is kept constant, even in case of power cycling. Important: No diesel engine should be subjected to air-side control.

While special T-pieces or mixing chambers with 0.5 to 1.0 times the engine displacement can serve as the diesel/biogas mixing chamber, at which a true mixing chamber offers the advantage of more thorough mixing.

Conversion according to the dual-fuel method is evaluated as follows:

— a quick & easy do-it-yourself technique

— will accommodate an unsteady supply of biogas

— well-suited for steady operation, since a single manual adjustment will suffice

— requires a minimum share of diesel to ensure ignition.

Conversion to spark ignition (Otto cycle)

involves the following permanent alterations to the engine:

— removing the fuel-injection pump and nozzle

— adding an ignition distributor and an ignition coil with power supply (battery or dynamo)

— installing spark plugs in place of the injection nozzles

— adding a gas mixing valve or carburetor

— adding a throttle control device

— reducing the compression ratio to E = 11–12

— observing the fact that, as a rule, engines with a precombustion or swirl chamber are *not* suitable for such conversion.

Converting a diesel engine to a biogas-fueled spark-ignition engine is very expensive and complicated — so much so, that only preconverted engines of that type should be procured.

Converting spark-ignition engines

Converting a spark-ignition engine for biogas fueling requires replacement of the gasoline carburetor with a mixing valve (pressure-controlled venturi type or with throttle). The spark-ignition principle is retained, but should be advanced as necessary to account for slower combustion (approx. $5°–10°$ crankshaft angle) and to avoid overheating of the exhaust valve while precluding loss of energy due to still-combustible exhaust gases. The engine speed should be limited to 3000 r.p.m. for the same reason. As in the case of diesel-engine conversion, a simple mixing chamber should normally suffice for continuous operation at a steady speed. In addition, however, the mixing chamber should be equipped with a hand-operated air-side control valve for use in adjusting the air/fuel ratio (opt. d = 1.1).

Table 5.23: Engine-conversion requirements for various duty and control modes (Source: Mitzlaff 1986)

Duty mode	Control mode	Conversion mode
Speed: constant *power: constant* e.g. for a pump with constant head and constant delivery	*Diesel or spark-ignition engine:* fixed manual adjustment; no readjustment necessary under normal circumstances	addition of a simple, manually adjusted mixing chamber
Speed: constant *power: variable* e.g. for a constant-frequency subject to varying power; or for a pump with constant head and varying delivery volume	Automatic speed control: *Spark-ignition:* electronic governor controls the throttle *Diesel:* fixed biogas fraction, with speed control via diesel intake governor	*Spark-ignition:* carburetor or gas-mixing valve with throttle; electronic control *Diesel:* Regulator and hand-adjusted mixing chamber
Speed: variable *power: variable* e.g. for powering various types of machines	*Spark-ignition:* by hand (if varying speed is acceptable) or electric with setpoint control *Diesel:* by hand via accelerator lever	*Spark-ignition:* electronic with set-point control, gas mixing valve or carburetor with throttle, plus regulator *Diesel:* simple, hand-adjusted mixing chamber

Converting a spark-ignition engine results in a loss of performance amounting to as much as 30%. While partial compensation can be achieved by raising the compression ratio to E = 11-12, such a measure also increases the mechanical and thermal load on the engine. Spark-ignition engines that are not expressly marketed as suitable for running on gas or unleaded gasoline may suffer added wear & tear due to the absence of lead lubrication.

Fig. 5.35: Various gas mixers for spark-ignition and diesel engines. 1 Air intake, 2 Air filter, 3 Biogas supply pipe, 4 Biogas control valve, 5 Mixing chamber (0.5-1 × piston displacement) 6 Throttle, 7 Mixing valve (Source: OEKOTOP)

adjustable mixing valve

T-piece   mixing chamber

to the engine
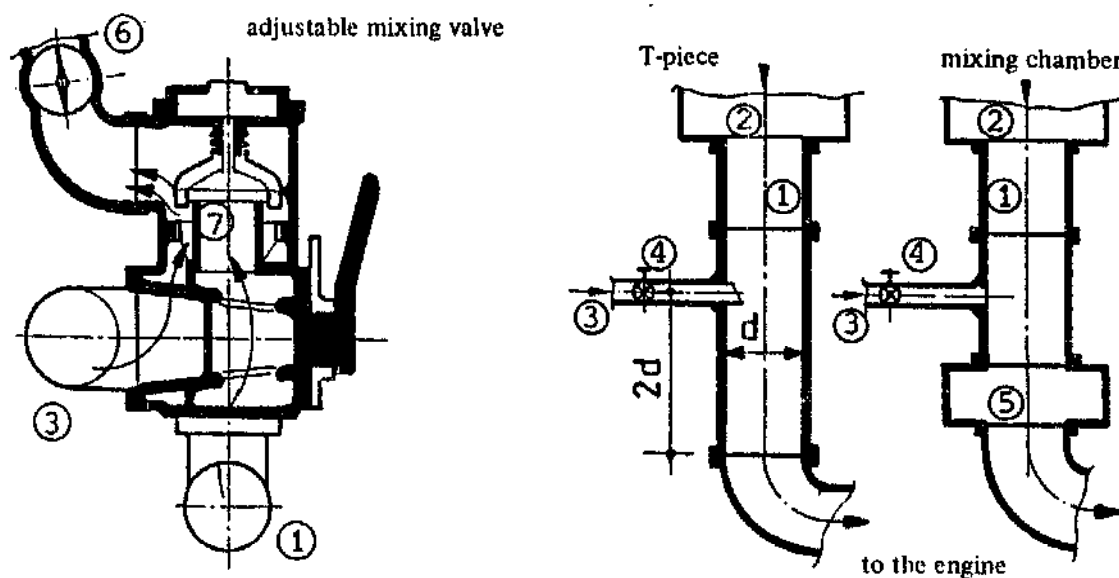
The speed control of converted spark-ignition engines is effected by way of a hand-operated throttle. Automatic speed control for different load conditions requires the addition of an electronic control device for the throttle.

The conversion of spark-ignition engines is evaluated as follows:

– Gasoline engines are readily available in the form of vehicle motors, but their useful life amounts to a mere 3000–4000 operating hours.

– The conversion effort essentially consists of adding a (well-tuned) gas mixer.

– Gasoline engines are not as durable as diesel engines.

Engine selection and operation

Speed

Since biogas burns relatively slowly, biogas-fueled engines should be operated at

– 1300–2000 r.p.m. (diesel)
– 1500–3000 r.p.m. (spark-ignition)

The standard speeds for such engines are 1500 and 3000 r.p.m. (50 Hz) or 1800/3600 r.p.m. (60 Hz) because of connecting a generator. For direct-power applications, i.e. a V-belt drive, the transmission ratio should ensure that the engine operates within its best efficiency range (= lowest fuel consumption) under normal-power conditions.

$$\frac{\phi \text{ engine-end pulley}}{\phi \text{ machine-end pulley}} = \frac{\text{speed of machine}}{\text{speed of engine}}$$

Consumption

Depending on the gas composition, barometric pressure and type of engine, the specific consumption will amount to 0.5–0.8 m^3/kWh, i.e. a 10-kW engine will use 5–8 m^3 biogas per hour. In a dual-fuel setup, the biogas consumption rate can be reduced by lowering the biogas fraction.
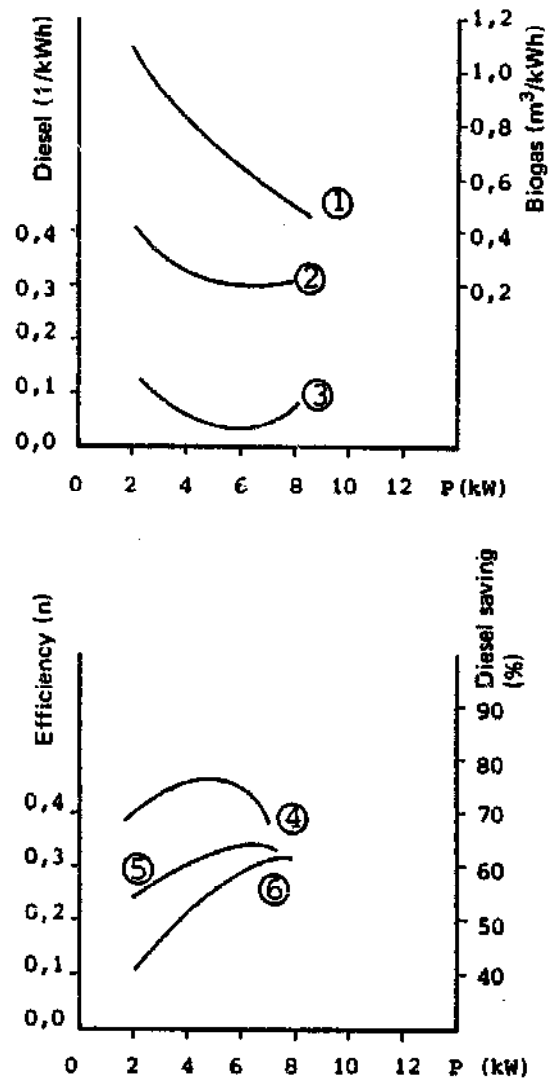
Fig. 5.36: Consumption of diesel and biogas by a 10-kW engine (1 cyl., 1000 ccm), 1300 m above sea level, running at 1500 r.p.m. 1 Biogas consumption in dual-fuel operation, 2 Diesel consumption in pure diesel operation, 3 Diesel consumption in dual-fuel operation, 4 Diesel saving, 5 Efficiency in diesel operation, 6 Efficiency in dual-fuel operation (Source: Mitzlaff 1986)

Maintenance and useful life

In contact with water, the H_2S content of biogas promotes corrosion. Consequently, adherence to the prescribed oil-change intervals is very important (after each 100 operating hours or so for vehicle spark-ignition engines). Dual-fuel engines should be started on pure diesel, with biogas being added gradually after about 2 minutes. For

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shutdown, the biogas fraction should be gradually reduced prior to stopping the engine. Any engine that has not been in operation for a considerable length of time should first be flushed out with scavenge oil (50% motor oil, 50% diesel oil) and filled with fresh oil. As long as extreme operating conditions are avoided, the engine can expected to achieve its normal useful life.

Exhaust-heat utilization

Internal-combustion engines have efficiency levels of 25–30% (gasoline engine) and 33–38% (diesel engine). A higher overall efficiency can be achieved by exploiting the heat content of the cooling water and exhaust, e.g. by:

– an exhaust heat exchanger (danger of H_2O-corrosion if the exhaust gas cools down to 150 °C or less)

– coolant heat exchanger (at coolant temperatures of 60–70 °C).

Fig. 5.37: Energy shares of an internal-combustion engine. 1 Energy input, 2 Dissipated energy (radiant heat and exhaust), 3 Useful exhaust energy, 4 Thermal energy in cooling water, 5 Mechanical power applied to crankshaft (Source: Mitzlaff 1986)
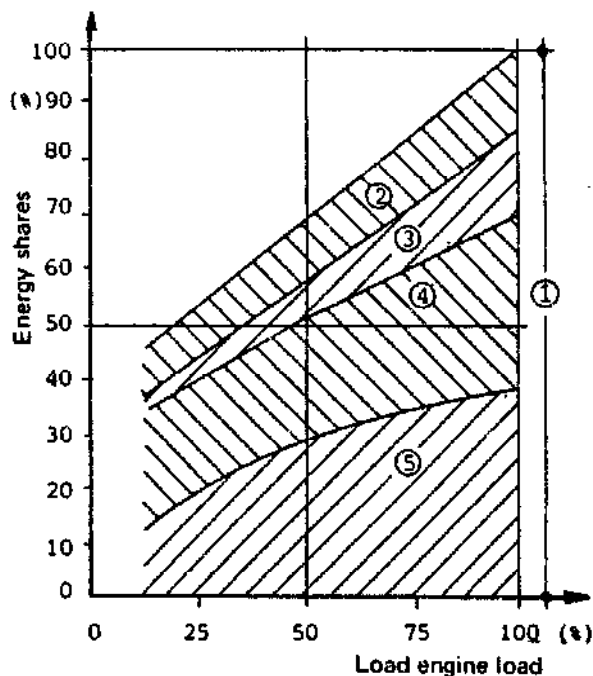
The recovered heat can be used for:
– heating utility water
– drying agricultural products
– space heating.

However, the requisite equipment/control effort makes heat recovery uneconomical except for large heavy-duty engines.

Motor-generators

The most frequent use for biogas-fueled engines is the generation of electricity. Suitable components include:

– asynchronous generators for system interconnection, i.e. the generator can only be operated in connection with a central power network. If the network breaks down, the generator cannot stay in operation. System control and network adaptation are relatively uncomplicated.

– synchronous generators for insular networks, i.e. an electronic control system on the generator stabilizes a constant power network.

Converting one type of generator to the other is very intricate and involves a complicated electronic control arrangement.

In selecting a particular type of motor-generator, one must give due consideration to the various operating conditions and network requirements (including the legal aspects of power feed-in).

Checklist for choosing a suitable engine

1. Define the energy requirement and speed of the machine to be powered;

2. Compare the biogas demand with the given storage capacity; if a shortage is possible, opt for the dual-fuel approach;

3. Select an engine with performance characteristics that are sure to provide the required power output in sustained operation in the optimal duty range:

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— diesel engines $\quad P_{engine} = P_{machine}/0.8$
— gasoline engines $\quad P_{engine} = P_{machine}/0.6$

This accounts for the fact that the continuous-duty power output is less than the nominal output. On the other hand, choosing an overly powerful engine would make the specific consumption unnecessarily high. Careful planning is very important in any project involving the use of biogas in engines; experienced technicians are needed to make the engine connections; and access to maintenance and repair services is advisable. Both the biogas plant itself and the engine require protection in the form of a low-pressure cutout that shuts down the latter if the gasholder is empty. Chapter 10.5 lists some recommended types of biogas engines and supplier addresses.

5.6 Measuring Methods and Devices for Biogas Plants

The purpose of conducting measurements on a biogas plant is to enable timely detection of developing problems, adjustment to optimum operating conditions, and gathering of practical data for comparison with those of other plants. The following variables can be measured quickly and easily:

— gas production via dry gas meter or by measuring the fill level of the gasholder
— weight of inputs via a hand-held spring scale
— temperature via an ordinary stem thermometer or electronic temperature sensor
— total-solids content by drying a sample at 104 °C and weighing the residue on a precision balance
— H_2S content of the gases via a gas test tube
— pH via litmus paper.

The contents of the substrate/slurry can only be determined by a special laboratory.

Various levels of precision are recommended, depending on the set objective and corresponding time, effort and equipment expenditure.

Observation by the user

Procedure
— measuring the gas consumption through daily checking of the calibration marks on the gasholder
— measuring the daily input quantities via defined-volume vessels
— measuring the air/slurry temperature with a thermometer.

Documentation
Daily notation of measured values.

Interpretation/results
Daily gas production as a function of substrate input and temperature.

Field testing by the extension officer

Procedure
— installation and daily reading of a dry gas meter to determine the rate of gas production
— random sampling of the CO_2 and H_2S contents of the biogas
— determination of quantities added by weighing the moist mass and water on a spring scale
— random sampling to determine the total solids content of the substrate
— measuring the digester temperature with the aid of a remote electronic thermometer
— measuring the ambient temperature with a mini-max thermometer
— determining pH levels via litmus paper
— laboratory testing to determine the C/N-ratio, volatile solids content and manurial quality of digested slurry.
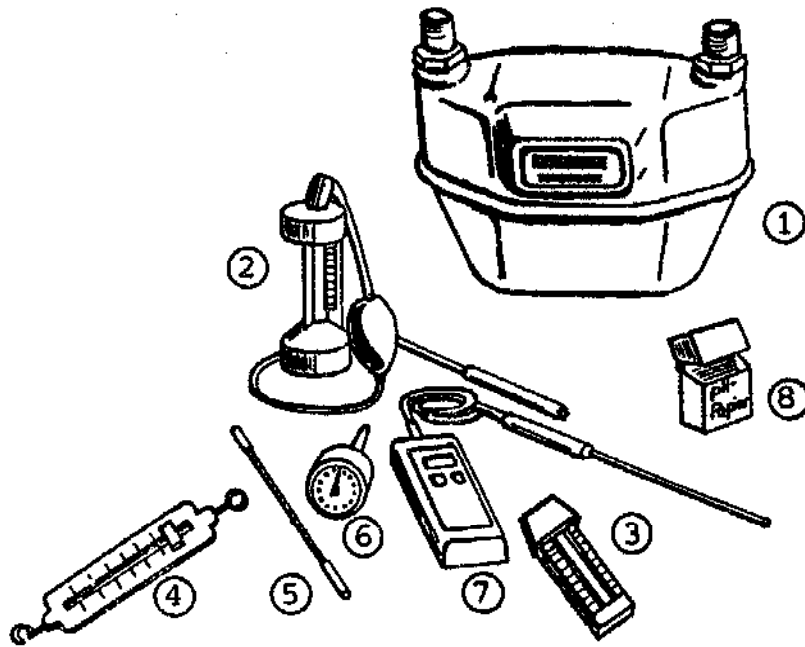
Fig. 5.38: Measuring instruments for biogas field tests. 1 Gas meter, 2 CO_2 tester, 3 Mini-max thermometer, 4 Spring scale, 5 Stem thermometer, 6 Insertable thermometer, 7 Electric remote thermometer, 8 Litmus paper (Source: OEKOTOP)

Documentation
Daily entry of measured values in a log book.

Interpretation of results
– time history of daily gas production as a function of temperature and substrate input

– time history of specific gas yield ($Gy = m^3$ gas/kg TS) and of specific gas production (m^3 gas/m^3 Vd) as a function of temperature
– time history of pH
– time history of maximum and minimum ambient temperatures, i.e. mean monthly and annual temperatures, plus extremes.

6. Large-scale Biogas Plants

Biogas technology, or better: anaerobic-process engineering, is becoming increasingly important as a means of treating and cleaning industrial organic waste materials and highly loaded organic wastewater.

This applies in particular to the following ranges of production:

— large-scale stock farming
— industrial processing of agricultural produce (refining of sugar, production of starch, winning of fibers, processing of coffee, generation of alcohol, slaughterhouses, etc.)
— industrial and urban refuse and sewage (manufacturing of paper, organic household waste, sewage sludge, biotechnological industries).

Most biogas plants used in those areas are large-scale plant systems with volumes ranging from several hundred to several thousand cubic meters.

Compared to aerobic treatment, anaerobic processes offer comparable performance with regard to purification capacity and conversion rates, but also stand apart from the former in that they:

— require less energy to keep the process going and to generate useful energy in the form of biogas, and
— produce less organic sludge, because the growth rate of anaerobic microorganisms is slower than that of aerobic microorganisms.

Consequently, anaerobic treatment of waste materials and wastewater offer some major advantages for a comparable initial investment. Nonetheless, much of the technology has not yet passed the testing stage.

Due to the size of plant, different objectives and special requirements concerning operation and substrates, the anaerobic treatment of waste materials and wastewater involves

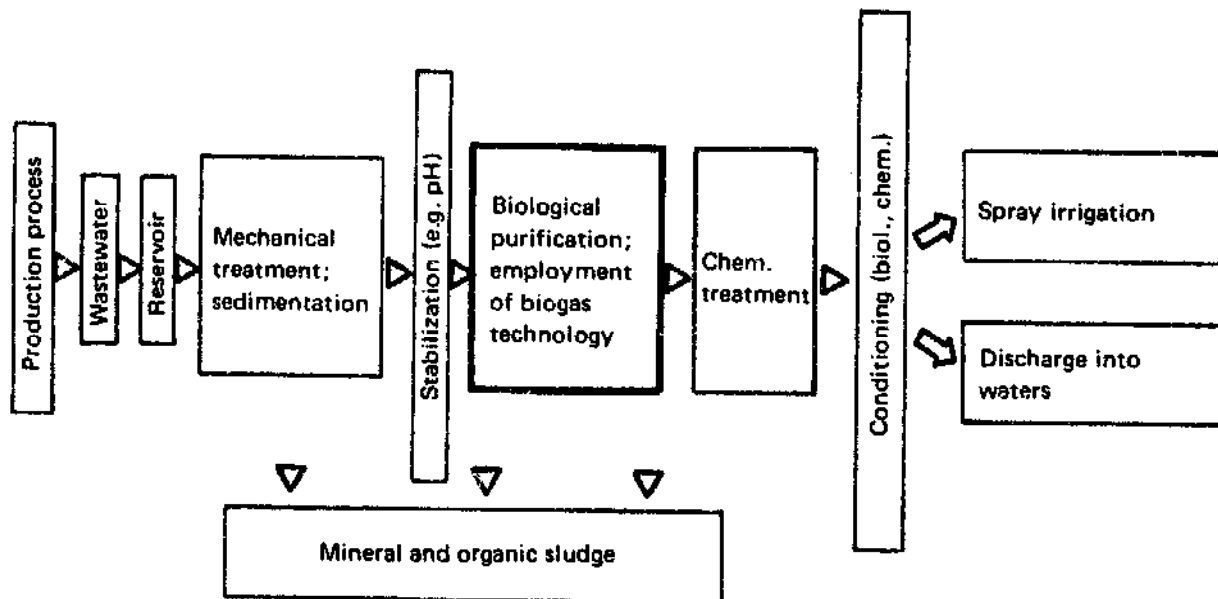Fig. 6.1: Basic principle of organic wastewater treatment (Source: OEKOTOP)

Table 6.1: Some examples of biogas production from agro-industrial residues and wastewater (Source: OEKOTOP, compiled from various sources)

Area of production	Retention time [d]	Digester loading [kg/m³ × d]	Gas production [m³/kg]	[m²/m³ × d]	Degradation rate [%]
Slaughterhouse	0.5– 8.5	1.2– 3.5 COD	0.3–0.5 COD	0.1–2.4	80 COD
Fruit and vegetables	32.0	0.8– 1.6 VS	0.3–0.6 VS	–	–
Olive-oil extraction	20.0–25.0	1.2– 1.5 TS	0.7 BOD	–	80–85 BOD
Whey	2.0– 5.0	6.4 BOD	0.9 BOD	5.5	92 BOD
Potato starch	–	7.5 COD	0.3–0.4 COD	–	90–95 BOD
Yeast factory	0.5– 0.7	1.0– 8.0 COD	–	0.5–4	60–70 COD
Sugar mill	0.2– 1.0	12.0–16.5 COD	–	–	87–97 COD
Milk processing	3.4– 7.4	0.7– 2.0 VS	0.1–0.4 VS	–	86–99 BOD
Molasses slop	10.0	3.9 VS	0.9 VS	3.5	97 BOD
Molasses distillery	1.2– 3.5	18.3 COD	0.6 COD	6.6	45–65 COD
Brewery	2.3–10.0	1.8– 5.5 TS	0.3–0.4 TS	–	–
Tannery	0.5	2.7–31.9 COD	–	–	80–91 COD
Pharmaceut.ind.	0.5– 2.0	0.2– 3.5 COD	0.6 COD	0.1–2.5	94–98 COD
Refuse + sewage sludge	11.0–22.5	1.2– 3.1 VS	1.0 VS	–	–
Refuse	25.0–30.0	0.7– 3.2 VS	0.1–0.4 VS	–	–
Cattle farming	15.0–35.0	0.5– 2.5 VS	0.2–0.4 VS	0.6–1.4	–
Pig farming	10.0–25.0	0.8– 4.1 VS	0.1–0.5 VS	0.8–2.1	–
Poultry farming	15.0–35.0	0.6– 3.6 VS	0.2–0.5 VS	0.7–1.8	–
Sewage sludge	20.0–30.0	1.2– 4.5 VS	0.1–0.6 VS	0.8–1.5	–

a different set of planning mechanisms, plant types and implementational factors. To go into detail on this subject would surpass the intended scope of this manual; besides, extension officers hardly need expect to be confronted with the job of planning such plants. Nevertheless, some basic information is offered here to give the reader a general grasp of what large-scale biogas technology involves.

In discussing the various waste-treatment options, differentiation is made between wastewater (organic – highly loaded) and waste materials/residues (organic solids).

Wastewater treatment

Organically contaminated wastewater contains mostly dissolved substances that are measured in terms of COD (chemical oxygen demand) and BOD (biochemical oxygen demand, i.e. oxygen required for mineralizing the organic contents).

The main purpose of wastewater treatment is to remove or mineralize the organic substances, i.e. to prepare them for release into a receiving body of water or the agricultural environment.

Anaerobic fermentation serves as the biological purifying process. Purification performance rates of up to 95% BOD are achievable. The choice of process and the achievable purification performance rates are determined by the type and composition of the substrate/wastewater. In general, dissolved organic substances are readily biodegradable. Retention times ranging from a few hours to a few days are not uncommon. On the other hand, some organic substances are hard to break down (paints, aromates, etc.), while others are toxic and/or capable of causing a shortage of nutrients and adverse medium characteristics (e.g. pH-shifts). A number of special-purpose processes have been developed for use in anaerobic wastewater treatment in order to compensate for

the high hydraulic loads and lack of bacterial colonization areas:

Contact fermenter

Digested slurry is recycled through a continuously stirred reactor in order to maintain a high level of bacterial concentration and, hence high performance. The contact process is a suitable approach for both mobile substrates and substrates with a high concentration of solids.

Upflow fermenter

An upflow-type fermenter with a special hydraulic configuration serves simultaneously as a suspended-solids filter with a high bacterial density and correspondingly high biodegradation performance.

Fluidized-bed fermenter

A vehicle (balls of plastic or clay) is kept "floating" in the fermenter to serve as a colonizing area for the bacteria.

Fixed-bed fermenter

A vehicle (plastic pellets or lumps of clay, rock or glass) provides a large, stationary colonization area within the fermenter. Fixed-bed fermenters are suitable for wastewater containing only dissolved solids. If the wastewater also contains suspended solids, the fermenter is liable to plug up.

Two-phase fermentation

The acidic and methanogenic phases of fermentation are conducted separately, each under its own optimum conditions, in order to maximize the fermentation rates and achieve good gas quality.

The treatment of wastewater marked by heavy organic pollution must always be looked upon as an individual problem that may require different processes from one case to the next, even though the initial products are identical. Consequently, trials must always be conducted for the entire chain: production process – purification – wastewater utilization – and energy supply/use.

Thanks to their uncomplicated, robust equipment, the contact process and fixed-bed fermentation stand the best chance of success in developing countries.

Waste materials/residues

The fact that practically identical production processes often yield residues that hardly resemble one another also applies to industrial waste materials. Here, too, pretrials and individual, problem-specific testing are called for in any case.

The potential range of organic waste materials is practically unlimited. Of particular interest for the purposes of this manual, however, are waste materials from factory farms and slaughterhouses.

Large-scale stock farming

The characteristics of dung from cattle, pigs and chickens were described in chapter 3.2. In factory farming, the dung yield is heavily dependent on the given type of fodder and how the stables are cleaned. Thus, pinpoint inquiries are always necessary.

The large quantities of substrate, often exceeding 50 m^3/d, lead to qualitative differences in the planning and implementation of large-scale plants, as opposed to small-scale plants. This has consequences with regard to substrate handling and size of plant:

– Daily substrate-input volumes of more than 1 m^3 cannot be managed by hand. Pumps for filling the plant and machines for chopping up the substrate are expensive to buy and run, in addition to being susceptible to wear & tear. In many cases, careful planning can make it possible to use gravity-flow channels for filling the plant.

– Plants of a size exceeding 100 m^3 usually cannot be made of masonry, i.e. the types of plant discussed in chapter 5 cannot be used.
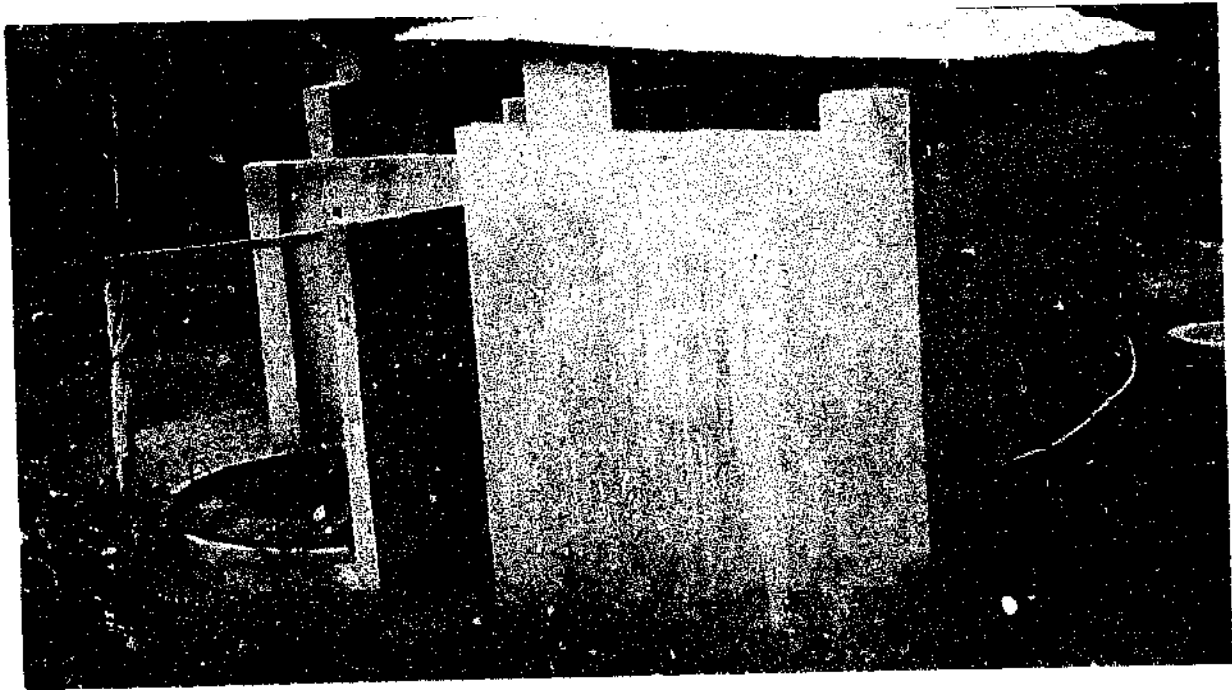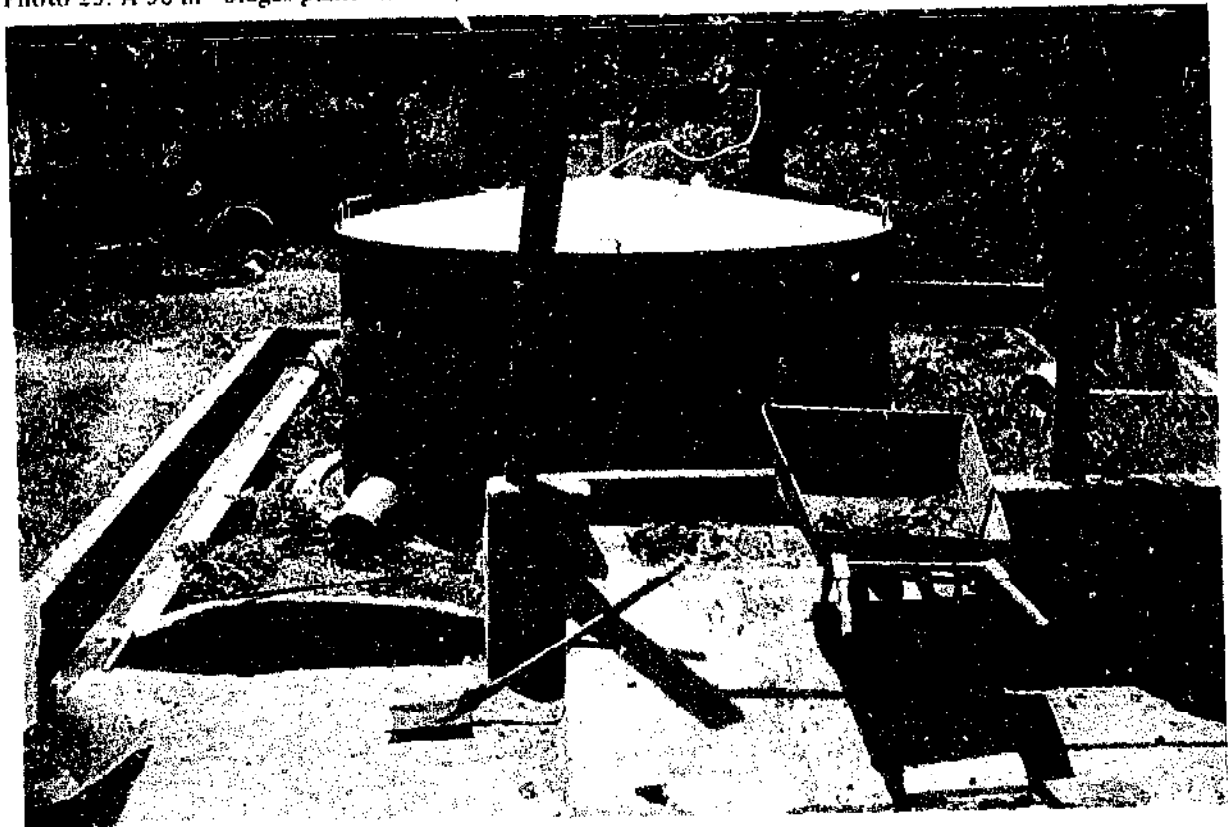
Photo 22: A night-soil biogas plant at a school in Burundi (Source: OEKOTOP)

Photo 23: A 30-m³ biogas plant on a large farm in Tanzania (Source: OEKOTOP, BEP Tanzania)
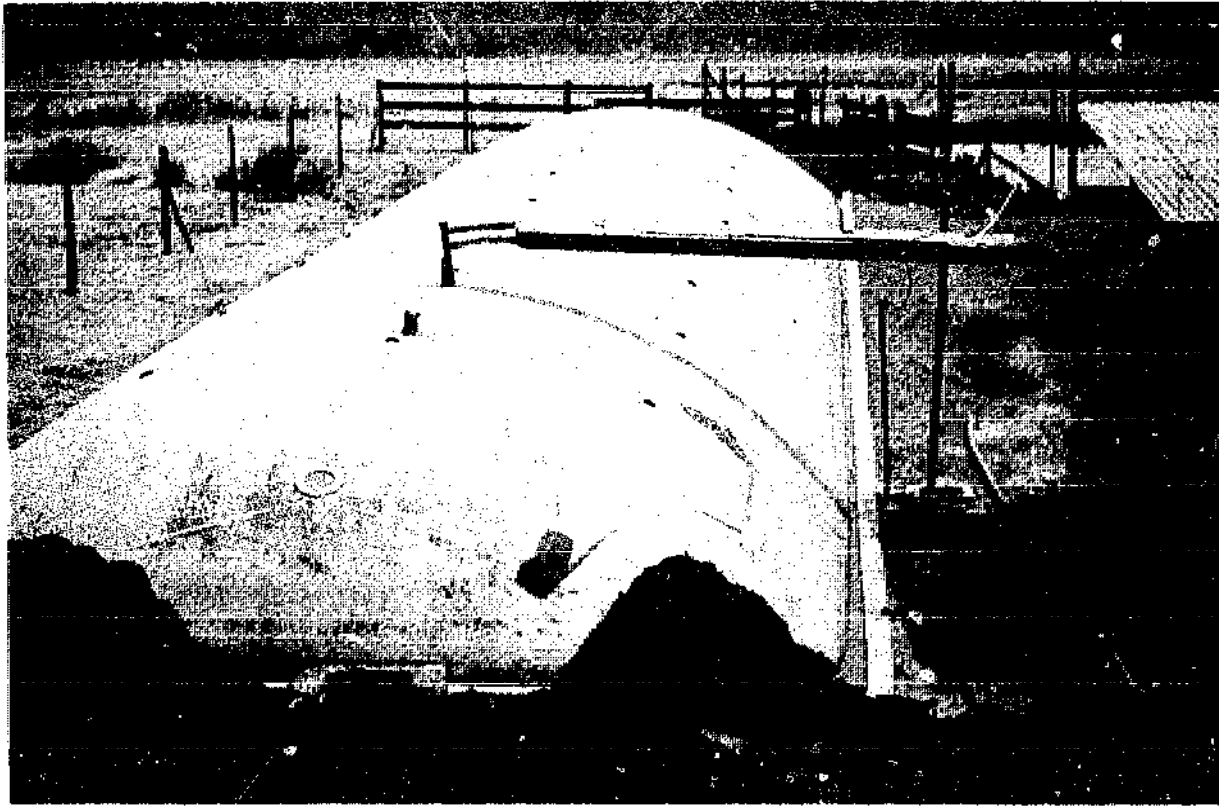
Photo 24: Large-scale biogas plant Ferkéssédougou – system OEKOTOP – in Côte d'Ivoire (Soure: OEKO-TOP)

The choice of plant is limited to either the mechanized types used in industrial countries or simple, large-scale plants. Experience shows that most simple, large-scale plants are

- of modular design,
- usually equipped with channel digesters,
- and require the use of substrate from which the scum-forming material has been removed in order to get by with either low-power mechanical mixers or none at all.

Since large-scale biogas plants produce accordingly large volumes of biogas, the generation of electricity with the aid of a motor-generator set is of main interest.

The two Ferkéssédougou biogas plants situated in the northern part of Côte d' Ivoire stand as examples of a successful large-scale biogas-plant concept based on a simple design. They have been in operation

at the local cattle-fattening station and slaughterhouse since 1982 and 1986, respectively, where they serve in the disposal of some of the excrements produced by an

Photo 25: Using biogas to generate electricity – a 15-kW motor-generator set in Ferkéssédougou (Source: OEKOTOP)
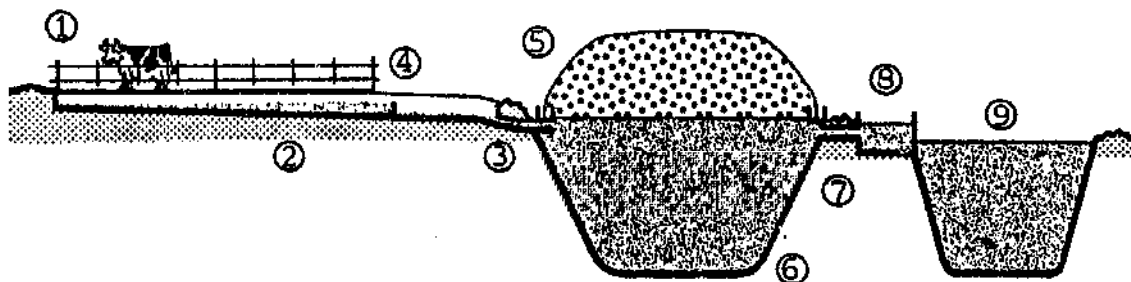

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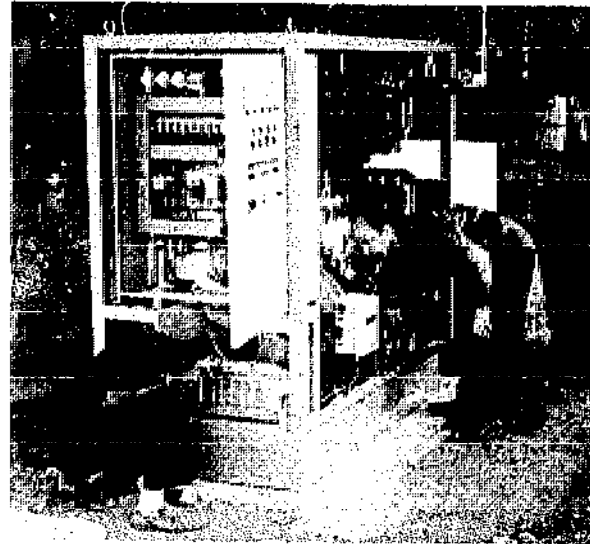
Fig. 6.2: Biogas plant in Ferkéssédougou – system OEKOTOP. 1 Cattle feedlot, 2 Manure gutter, 3 Feed-pipe, 4 Sluice, 5 Rubber-sheet gasholder, 6 Earth-pit digester, 7 Discharge pipe, 8 Impounding weir, 9 Slurry storage (Source: OEKOTOP)

average number of 2500 head of cattle. The plant consists of a simple, unlined earth-pit digester with a plastic-sheet cover serving as gasholder. The gas is used for generating electricity, heating water and producing steam.

At present, some 20% of the slaughter-house's electricity requirement is covered by the biogas plants, and the biogas-driven steam sterilizer saves 50 000 l diesel fuel each year. The total initial investment amounting to 60 million F.CFA yields annual savings of approximately 12 million F.CFA after deduction of the operating costs (1 DM = 150 F.CFA).

The Ferkéssédougou biogas plants demonstrate how even large-scale installations can keep biogas technology cost-efficient by relying on simple designs, e.g. large digester volume despite low cost of construction.

Slaughterhouses

The proper disposal of paunch and intestinal contents (fecal matter), dung and urine and, in some cases, blood and offal is not always ensured in slaughterhouses. Such residues can be put to good use in a biogas plant, since:

— the energy demand and the substrate incidence are extensively parallel and usually involve short distances for transportation;

Table 6.2: Technical data of the Ferkéssédougou biogas plant (Source: OEKOTOP)

	Biogas plant I	Biogas plant II
No. of animals	700 head of cattle in 12 feedlots	
Digester volume	400 m³	810 m³
Gasholder volume	80 m³	>600 m³
Slurry storage volume	300 m³	3500 m³
Retention time	40–2. days	40–22 days
Daily substrate input[1]	10–18 m³/d	20–38 m³/d
TS-content	4–8%	
Daily gas production	250 m³/d	450 m³/d
Specific gas production	0.6 m³/m³ Vd	0.55 m³/m³ Vd
Gas utilization	MWM gas-powered motor-generator set 15 kWel	Deutz gas-powered motor-generator set 32 kWel, with exhaust heat recovery for heating water
Operating time	22 h/d	10 h/d
Power generation	270 kWh/d	245 kWh/d Combination gas-oil burner for steam sterilizer, 130–355 kW

[1] Fluctuation due to seasonal factors (rainy/dry season)

Table 5.3: Slaughterhouse waste quantities (Source: OEKOTOP)

Type of waste	Cattle	Sheep	Pigs
Stomach contents	11.6%[1]	4.3%[1]	2.8%[1]
Intestinal contents	3.3%[1]		
Blood	~14 kg	~2 kg	~4 kg
Offal	2–5 kg	0.5–1 kg	1–1.5 kg
Dung (without fodder)	5 kg	0.8 kg	1.5 kg

[1] Expressed as percentages of live weight

— the biogas technique is more cost-efficient and yields more energy than aerobic processes, so that most slaughterhouses could cover their own energy demand with such a plant.

Slaughterhouses in developing countries span a wide size range. Consequently, various techniques are needed for treating and/or disposing of waste materials and wastewater. While little experience has been gained to date in connection with the disposal of slaughterhouse wastes via biogas technology, the following assessment can nonetheless be arrived at:

— *Small, village-scale slaughterhouses*
in which 50–100 animals are slaughtered each week can make use of simple agricultural biogas plants like those discussed in chapter 5 for disposing of all offal and other residues, and the digested slurry can be used as agricultural fertilizer.

The main problem in such plants is the formation of a thick layer of scum made up of the contents of paunches and fecal matter. For that reason, and in order to achieve good hygiene, retention times of 100 days or more are considered practical.

— *Medium-sized slaughterhouses (200–500 slaughterings per week)*
Here, too, biogas plants are able to provide complete disposal, although large-scale types like those used in Ferkéssédougou are required. Sometimes, it is a good idea to separate the solid wastes from the wastewater and possibly compost the solids.

— *Large-scale slaughterhouses*
Most such slaughterhouses are quite similar to those found in European cities and are usually located in urban areas. Consequently, proper waste disposal and wastewater purification call for integrated concepts in line with European standards.

7. Plant Operation, Maintenance and Repair

The main objective of any plant owner/user is to have a well-functioning biogas plant that involves a modest amount of work for operating it and requires very little effort and expense for maintenance and repair in the long run. Smooth running of a biogas plant is dependent on good information and careful planning and construction. Operating errors and false expectations are the most frequent causes of plant outage.

7.1 Commissioning of Biogas Plants

The commissioning procedure for a biogas plant includes:
— inspection and final acceptance of all components
— initial filling
— starting the plant
— user familiarization

Inspection and final acceptance

Prior to filling the plant, all components must be carefully inspected for proper function and suitability for acceptance. Of particular importance at the time of final acceptance is seal testing of the digester, gasholder and gas pipes.
It must be kept in mind that the seal tests described below are very laborious without pumps (e.g. hauling of more than 10 m³ water) and may not even be feasible if water is scarce, in which case such testing must be dispensed with. The time and effort involved must be weighed against the risk of having to empty the plant after completely filling it with slurry. In either case, it is very advisable to use a motor pump.

Water-seal testing
Fill the entire digester with water and check the fill level in all components.
Once all components have become saturated with water (after about 1 day), refill to the zero line, wait one day, and then remeasure. If the water loss amounts to less than 2% of the digester volume, the plant may be regarded as leaktight.
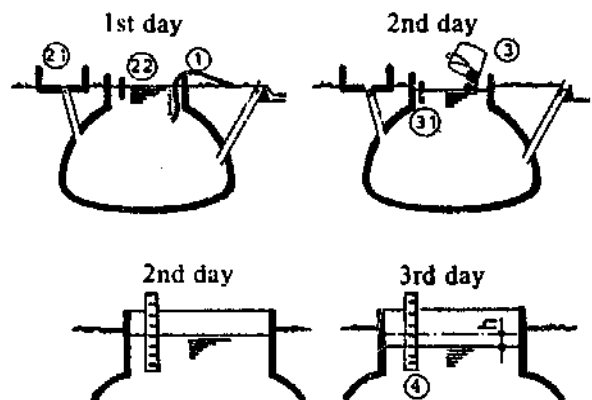
Seal testing (water and gas) of a fixed-dome plant
Fixed-dome plants are regarded as leaktight if the water-seal test shows less than 2% water loss, and the gas-seal test shows less than 5% gas loss.

Gas-seal testing of a floating-drum plant
In the case of floating-drum plant, only the metal gasholder must be subjected to gas-

Fig. 7.1: Water-seal testing of a digester. 1 Fill the plant with water; Check the fill levels: 21 Inlet – no water in the mixing pit, 22 Digester – at least 10 cm neck height above water level. 3 Refill to compensate for moisture absorbed by the masonry. 31 Mark the water level. 4 Measure the drop in water level as basis for calculating the water loss $(W_1 = \pi r^2 \times h)$. 5 Repeat measurements as necessary. (Source: OEKOTOP)
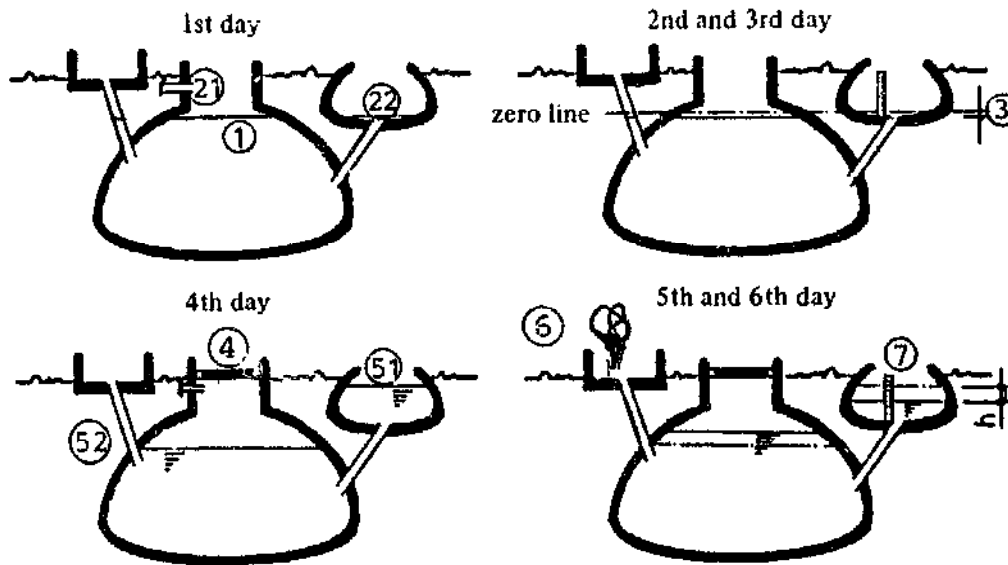
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Fig. 7.2: Seal testing (water and gas) of a fixed-dome plant. 1 Fill the plant up to the zero line; Check the fill levels: 21 Gas extraction points at least 10 cm above discharge level, 22 Water level in the displacement pit. 3 Perform water-seal test and level-drop check (cf. fig. 7.1). 4 Close the entry hatch. 5 Fill with gas up to maximum allowable plant pressure a) with air (pump), b) with exhaust gas (vehicle exhaust), 51 . . . until the displacement pit overflows, or 52 . . . until gas bubbles out of the inlet pipe. 6 Refill the plant to compensate for saturation losses. 7 Measure the level drop (h) after one day, and calculate the gas losses. (Source: OEKOTOP)

seal testing; any leaks are detected with the aid of soap water.

Pressure testing of the gas pipe
The test must be performed while all gas-

pipe connections are still accessible. Pressurize the gas pipe with the aid of a test pump or by placing weights on the gasholder. If there is no noticeable loss of gas after one day, the pipe may be regarded as gastight.

Fig. 7.3: Gas-seal testing of a metal gasholder. 1 Place the gasholder in position with the gas valve closed. 2 Mark the top edge of the digester neck on the gasholder. 3 Check the location of the mark one day later. 4 If the mark is found to have dropped by 1–3 cm, use soapy water to check for leaks in the gasholder. (Source: OEKOTOP)
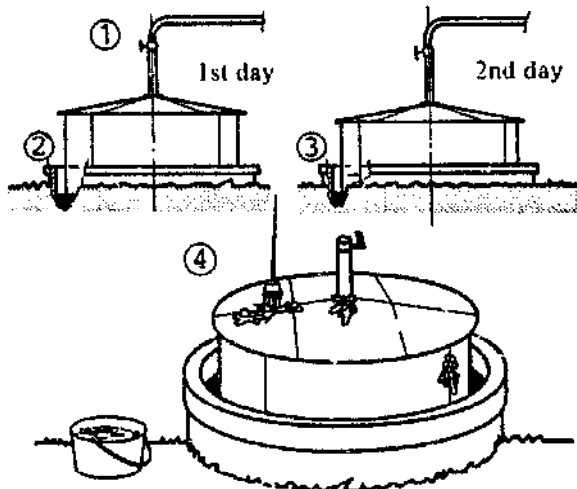
Fig. 7.4: Pressure testing a gas pipe. 1 Close all gas valves and fill the water trap. Find the maximum pipe pressure, i.e. how high the pressure in the pipe can go until the water trap blows off (not more than 50 cmWG). 2 Adjust the test pressure with the aid of a manometer-equipped test pump or the gasholder (10% below max. pressure). Check the pressure loss after one day. 3 Use soapy water to detect leaks. (Source: OEKOTOP)
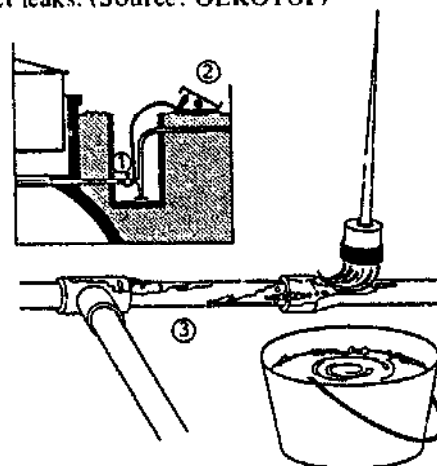
Initial filling of the plant

The initial filling for a new biogas plant should, if possible, consist of either digested slurry from another plant or cattle dung. It is advisable to start collecting cattle dung during the construction phase in order to have enough by the time the plant is finished. When the plant is being filled for the first time, the substrate can be diluted with more water than usual.

Starting the plant

Depending on the type of substrate in use, the plant may need from several days to several weeks to achieve a stable digesting process. Cattle dung can usually be expected to yield good gas production within one or two days. The breaking-in period is characterized by:

— low-quality biogas containing more than 60% CO_2
— very odorous biogas
— sinking pH and
— erratic gas production.

The digesting process will stabilize more quickly if the slurry is agitated frequently and intensively. Only if the process shows extreme resistance to stabilization should lime or more cattle dung be added in order to balance with pH. No additional biomass should be put into the biogas plant during the remainder of the starting phase. Once the process has stabilized, the large volume of unfermented biomass will give rise to a high rate of gas production. Regular loading can commence after gas production has dropped off to the intended level.

As soon as the biogas becomes reliably combustible, it can be used for the intended purposes. Less-than-optimum performance of the appliances due to inferior gas quality should be regarded as acceptable at first. However, the first two gasholder fillings should be vented unused for reasons of safety, since residual oxygen poses an explosion hazard.

User familiarization

The plant owner should be familiarized with the details of plant operation and maintenance at the time of commissioning. It is important that he be not only familiarized with the theory of function but given ample opportunity to practice using all parts of the plant. The user-familiarization procedure should be built up around an operational/maintenance checklist (cf. table 7.2).

Table 7.1: Checklist for the inspection and acceptance of biogas plants (Source: OEKOTOP)

Check item	Nonconformance	Remedy	Remarks
1 Interim inspection prior to backfilling			
Site	• unsuitable	• dismantle/demolish the plant	
Digester masonry	• cracked/broken bricks/ stones	• demolish the masonry	Fixed-dome plants in particular call for high-quality work. Tearing down the plant at this point is often the least-painful solution
	• seriously false dimensions		
	• improperly jointed masonry	• fix with mortar, incl. foundation	
inlet/outlet	• false configuration	• demolish	
pipes	• poor backfilling	• refill	

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Check item	Nonconformance	Remedy	Remarks
II Final inspection and acceptance			
Rendering in digester/ gasholder	• cracks, sandy rendering, low strength, cavities, poorly worked edges and coving	a) for the gas space of a fixed-dome plant: replace rendering b) for the slurry space: repair or add a new layer of rendering (usually sufficient)	Ensure high-quality workman-ship for fixed-dome plants
Masonry seal coats	• cracks, flaws, thin spots, voids	• renew the coating	(applies only to fixed-dome plants)
Mixing pit/slurry sotre/displacement pit	• cracks, poor workmanship	• demolish or repair	
Inlet/outlet pipes	• plugged, poorly worked transitions	• remove mortar plug, repair with mortar/ concrete	
Earth fill	• insufficient fill height • poorly compacted	• recompact, add earth	
Water-fill check of all component heights (relative): inlet, outlet, digester, gas-holder cf. chapter 7.1	for *floating-drum plants*: • water in mixing pit, too low; water spills over the digester, i.e. digester too low; outlet too low for *fixed-dome plants*: • water above gas zero line • water in mixing pit • water in displacement pit	• shorten the outlet • add wall height to digester • lengthen the outlet • alter the elevation of the a) gas outlet b) displacement pit • alteration too much trouble • alteration too much trouble	Differentiation must be made between nonconformances that impair the plant's function and nonconformances that merely prevent optimal utilization
Seal testing (see chapter 7.1 for details)	for *floating-drum plants*: • water loss < 2% • water loss > 10% for *fixed-dome plants*: • water loss < 2% (pressureless) > 10% • water loss < 5% (pressurized) > 10%	• acceptable as is • repair masonry • acceptable as is • repair masonry • acceptable as is • repair masonry	In case of doubt, locate and repair all defects, even if it seems like a lot of trouble at the moment; repairs at a later date would be more troublesome!
Gasholder (of floating-drum plants only)	• false dimensions, wrong grade of steel, • faulty welds • faulty painting	• reject gasholder, build new one • repair welds • repaint	
Gas valves	• stuck valves • missing valves • false water trap	• repair or replace	Check carefully; defects most likely in the gas system
Gas pipe	• false gradient • leak found upon pressure testing • poor workmanship	• re-install • repair leaks • re-install	
Gas appliances	• functional defects	• repair or replace	

7.2 Plant Operation

The operation of a simple biogas plant is relatively uncomplicated. The user must be given all the information and practical assistance he needs before and during the early phases of plant operation.

Collecting substrate

The collection of substrate is a simple matter when combined with work that has to be done anyway, e.g. cleaning the stables. It can be made even easier by arranging for the manure to flow directly into the mixing pit. Experience shows that it is not a good idea to gather dung from fields, roads, etc. or to go to the trouble of elaborately chopping up or otherwise preprocessing plant material for use as substrate. The work involved is usually underestimated, while the motivation is overestimated.

Photo 26: Reading the gas pressure of a fixed-dome plant (Source: OEKOTOP)

Filling the plant

Filling means: mixing the substrate with water, removing bouyant materials, allowing the fill material to warm up, flushing it into the digester, and removing sand and stones. The simple mixing pit shown in figure 5.16 can handle a daily fill quantity of up to 500 l.

Digested-slurry storage/utilization

The further processing of digested slurry is a critical point in that it can be quite toilsome (cf. chapter 3.4).
In designing the plant, care must be taken to ensure that the slurry store will be large enough. Fixed-dome plants in particular should be equipped with an overflow, so that the digested slurry does not have to be hauled away every day.

Table 7.2: Checklist for the daily operation and regular maintenance of biogas plants (Source: OEKOTOP)

Daily activities:
- fill the plant
- clean the mixing pit
- agitate the digester contents
- check the gas pressure
- check the gasholder contents
- check the appearance and odor of the digested slurry

Weekly/monthly activities:
- remove/use the digested slurry
- clean and inspect the gas appliances
- check the gas valves, fittings and appliances for leaks
- inspect the water trap

Annual activities:
- inspect the digester for scum formation and remove as necessary by opening the plant
- inspect the plant for water tightness and gas tightness
- pressure-test the gas valves, fittings and pipes
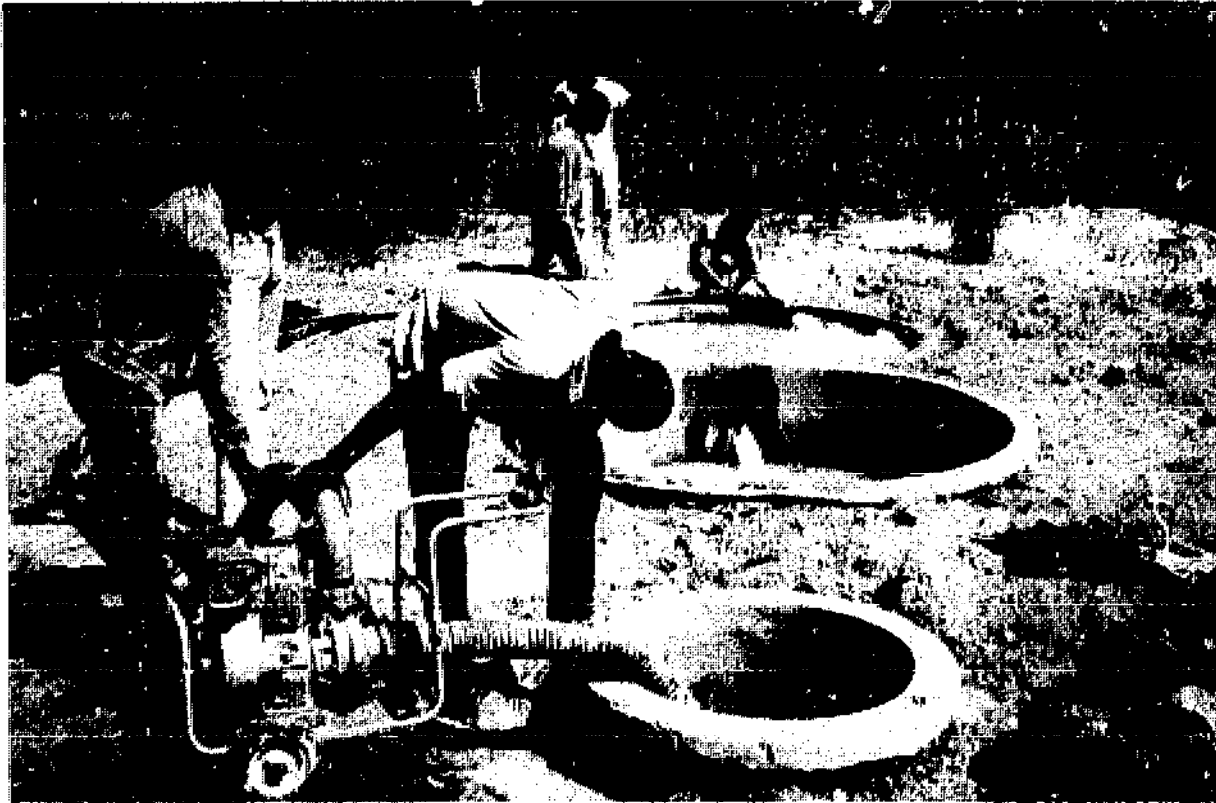- check the gasholder for rust and repaint as necessary

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Photo 27: Emptying the biogas plant after pressure testing (Source: BEP Burkina Faso)

Monitoring the process

If the plant is properly started before being handed over to the user, it may be assumed to be in proper working order. The user will have become familiar with what optimum plant operation involves. This is very important, because from then on he himself will have to watch for any appreciable changes in how the plant functions; the main indication of a beginning malfunction is a change in the daily gas output.

Photo 28: Painting the gasholder (Source: OEKO-TOP/BEP Caribbean)

7.3 Plant Maintenance

The maintenance scope for a biogas plant includes all work and inspections needed to ensure smooth functioning and long service life. To the extent possible, all maintenance work should be done by the user.

Biogas plants can develop a number of operational malfunctions. The most frequent problem, "insufficient gas production", has various causes. Often enough, it takes the work of a "detective" to locate and remedy the trouble. It may be necessary to experiment with and monitor the plant for months on end in cooperation with the user.

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Table 7.3: Checklist for troubleshooting in case of insufficient gas production (Source: OEKOTOP)

Quantity and quality of substrate
- low/less daily input
- excessive dilution with water
Ascertain by control measurements

Gas system leaks
- gasholder
- gas pipe
- valves and fittings
Ascertain by checking all components and connections for leaks with the aid of soapy water

Disturbance of the biological process
Indications:
- heavy odor
- change of color of digested material
- drop in pH

Possible remedial measures:
- inspect the quality of the substrate
- stop biomass until the process returns to normal
- stabilize the pH, e.g. with lime
- add cattle dung or healthy slurry
- investigate the user's filling methods to determine if pollutants or noxious substances (detergents, pesticides, etc.) are getting into the plant

7.4 Plant Repair

Repair measures for biogas plants (cf. table 7.5) are necessary in case of acute malfunctions and as indicated by routine monitoring. Repair measures exceeding simple maintenance work usually require outside assistance, since the user himself may not have the necessary tools or know-how.

It is advisable to have the annual maintenance work mentioned in chapter 7.3 performed by external artisans with prior experience in biogas technology. Such maintenance and repair work should be ordered on a contract basis. Past project experience shows that professional biogas repair and maintenance services can be very important for ensuring long-term plant performance. Such services should include general advice, functional testing, troubleshooting, spare-parts delivery and the performance of repair work.

Table 7.4: Simple-plant malfunctions and remedial measures (Source: OEKOTOP)

Problem	Possible cause	Countermeasures
Plugged-up inlet pipe	fibrous substrate	use rod to unplug the pipe
Stuck gasholder	floating scum	1. turn the gasholder 2. take off the gasholder and remove the scum
Tilted gasholder	broken guideframe	repair
Low gas production, poor gas quality	cf. table 7.3	cf. table 7.3
Receding slurry level	leak in plant	repair
Inadequate gas storage in fixed-dome plants	leak in gasholder	repair
Stuck gas cocks	corrosion	apply oil, operate repeatedly
Leaky gas pipe	corrosion, inferior workmanship	repair
Sudden loss of gas	- broken gas line - blown-off water trap - open gas cock	repair refill with water close
Pulsating gas pressure	water in the gas pipe plugged-up gas pipe	pump out the pipe, relocate that section of pipe push rod through pipe
Malfunctioning gas appliances	cf. chapter 5.5.3	cf. chapter 5.5.3
Structural damage	cf. table 7.1	cf. table 7.1

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Table 7.5: Potential repair situations for simple biogas plants (Source: OEKOTOP)

Damage	Detection	Remedial measures
Damaged masonry and rendering	Inspection of open plant, subsiding slurry level, seal test	Inspect the plant and repair any damage; tear down the plant if large cracks are found
Damaged or broken inlet/outlet pipe	(see above)	Replace pipe, repair connection to masonry
Damaged/leaky fixed-dome plants	Gas seal test, visual inspection of open plant	Repair rendering, renew seal coatings
Damaged/corroded gasholder	High gas losses, seal test	Replace gasholder, renew weldings
Broken guide frame	Tilted/immobile gasholder	Remove gasholder, repair guide frame
Leaky/broken/corroded gas pipe	High gas losses, gas seal test of pipe	Locate damage, repair or replace as necessary
Damaged valves/fittings	Functional inspection	as a rule: replace
Damaged gas appliances	Functional inspection	cf. "Gas appliances"

7.5 Safety Measures

Biogas is a combustible, explosive gas. Its safe handling and use can be ensured, or at least promoted, by:

- educational measures and operating instructions
- good, careful planning and execution
- timely detection of damage and gas leaks
- installation of safety equipment

Safety aspects of planning and implementation

The following basic rules should be adhered to:

- plant located outside of buildings used for other purposes, e.g. stablings
- underground installation of pipes
- no use of hoses
- careful installation and regular inspection of gas pipes
- regular inspection of gas appliances
- good ventilation of rooms containing gas appliances without safety pilots
- installation of safety stop valves – one directly on the plant, and another on each appliance.

Educational measures and operating instructions

The user must be made fully aware of the explosive nature of biogas, possibly by way of demonstration (e.g. by producing a flash flame). He must learn by heart the following basic rules:

- Never leave an open flame unattended!
- Always close the gas and safety valves of each appliance properly and immediately after each use!
- Close the plant's safety valves each night and whenever the plant is left unattended!

Experience shows that leaks and open gas cocks can be detected very quickly, i.e. before an explosive mixture forms, by watching for the conspicuous odor of unburned biogas.

Safety devices

As long as the above safety aspects are adhered to, small biogas plants in rural areas require few or no special safety devices, the one major exception being appliances that operate on their own, i.e. refrigerators, radiant heaters, etc., in which case the use of safety pilots is obligatory.

8. Economic Analysis and Socioeconomic Evaluation

8.1 Procedures and Target Groups

Any decision for or against the installation and operation of a biogas plant depends on various technical criteria as well as on a number of economic and utility factors. The quality and relevance of those factors are perceived differently, depending on the respective individual intrest:

– Users want to know what the plant will offer in the way of profits (cost-benefit analysis) and other advantages like reduced workload, more reliable energy supplies or improved health and hygiene (socioeconomic place value).

– Banks and credit institutes are primarily interested in the economic analysis as a basis for decisions with regard to plant financing.

– Policy-makers have to consider the entire scope of costs and benefits resulting from introduction and dissemination, since their decisions usually pertain to biogas extension programs instead of to individual plants.

Fig. 8.1: Basic elements of an economic analysis (Source: OEKOTOP)
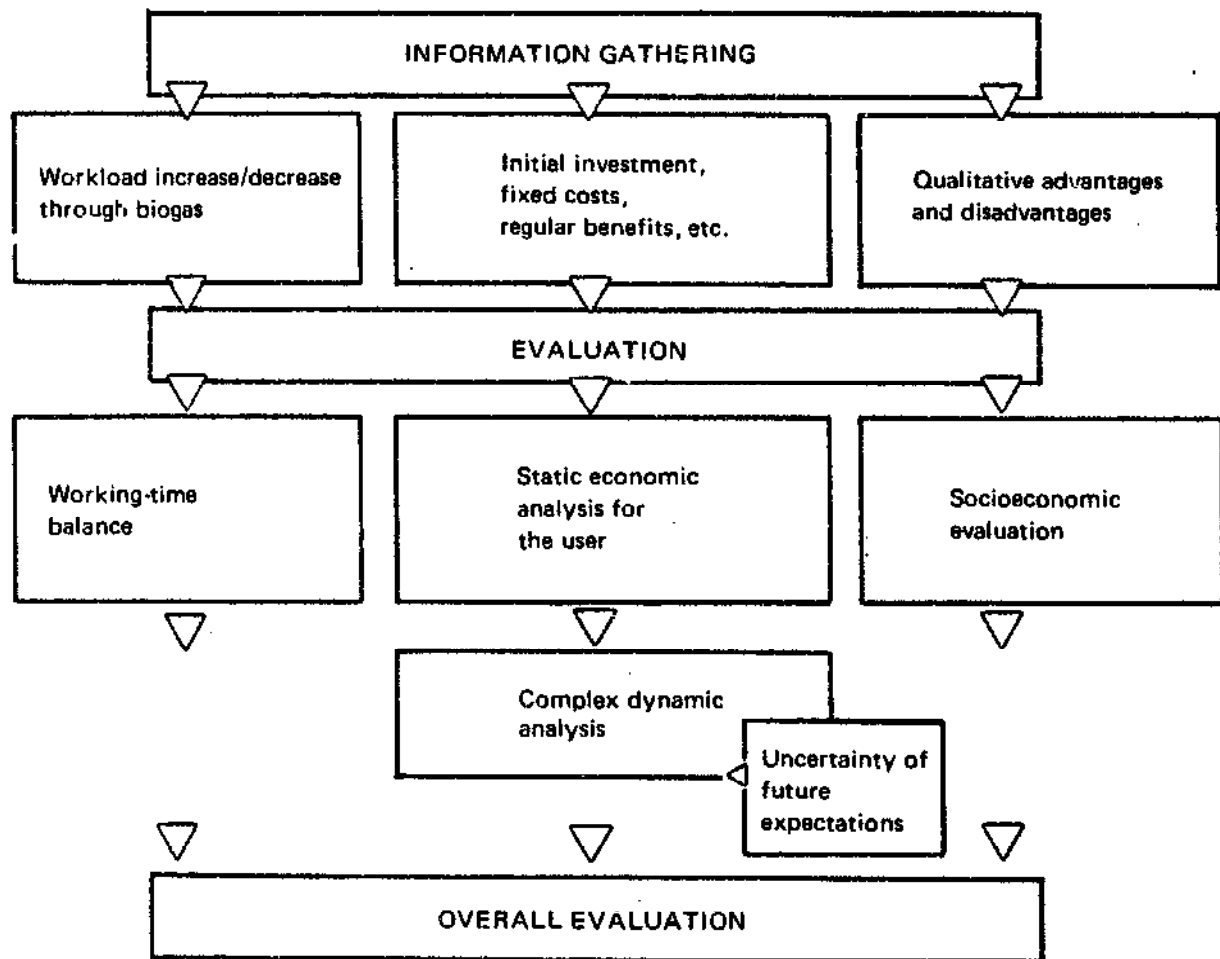
The evaluation of biogas plants must include consideration not only of the monetary cost/benefit factors, but also of the ascertainable nonpecuniary and unquantifiable factors. Time and again, practical extension work with the owners of small and medium-sized farms shows that a purely monetary approach does not reflect the farmers' real situation. For a farmer who thinks and works in terms of natural economic cycles, knowing how many hours of work he stands to save is often more important than knowing how much money he stands to gain. A similar view is usually taken of the often doubtful monetary evaluation of such a plant's qualitative and socioeconomic impact.

Figure 8.1 surveys the essential parts of an economic analysis. In practice, however, the collecting of information and data can present problems: experience shows, for example, that an exact breakdown of cost and benefits can hardly be arrived at until the plant has been in service long enough for the user to have gained some initial experience with its operation. Economic *prognoses* therefore should give due regard to such limitations by including calcu'ations for various scenarios based on pessimistic, average-case and optimistic assumptions. Consequently, the data stated in the following calculations and considerations are

intended to serve only as reference values. Any attempt to convert local plant & equipment costs into DM-values is seriously complicated by the fact that exchange rates are often set more or less arbitrarily and that the figures used may derive from unstable black-market prices.

8.2 Working-time Balance

For the users of family-size plants – primarily the operators of small to medium-size farms – the following three elements of the biogas plant evaluation have the most relevance:
– working-time balance
– micro-economic analysis and
– socioeconomic and qualitative considerations.

Working-time balancing is most important when the farm is, at most, loosely involved in cash-crop markets, so that the cost/benefit factors are more likely to be reflected in terms of hours worked, as in money.

Table 8.1 exemplifies a comparison of time expenditures for a farm with a biogas plant and for a similar one without a biogas plant. The unit of calculation is hours worked per year (h/a) by the farmer and his family. Any expenses for external assistance, e.g. "hired hands", appear only in the monetary (cash-flow) calculation (cf. chapter 8.3).

Table 8.1: Comparison of working time with and without biogas utilization (Source: OEKOTOP)

Working time with biogas plant	h/a	Working time without biogas plant	h/a
Planning/know-how acquisition	. . . . .	Mucking out the stables	. . . . .
Plant construction and installation of appliances	. . . . .	Hauling off/disposal of organic wastes	. . . . .
		Collecting, hauling and preparing fuel	. . . . .
Feeding/collecting manure	. . . . .	Cooking	. . . . .
Fetching water	. . . . .	Cleaning and repair of fireplace	. . . . .
Cooking	. . . .	Spreading of NPK-fertilizer	. . . . .
Maintenance and repair work	. . . . .	Tending of animals	. . . . .
Spreading of digested slurry/fertilizing	. . . .		
Tending of animals	. . . . .		
Total	. . . . .	Total	. . . . .

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The best indication of a successful biogas plant is a significant reduction in the average amount of time worked – especially by women and children who tend the plant and cook with the gas. If, for example, the family used to cook on wood gathered on the way back from the fields, a practice that involved little extra work, biogas technology can hardly expect to find acceptance under the heading "time saved".

The actual value of time saved depends not only on the quantity saved but also on the quality, i.e. whose workload is reduced at which time of day.

Real-time savings let the target group:
– expand their cash-crop and/or subsistance production
– intensify and improve their animal-husbandry practice
– expand their leisure time and have more time for their children, education, etc.

It should be noted that all time expenditures and time savings pertaining to anyone participating in the farm/household work, and which can be expressed in real monetary terms as cash-flow income or expenses must appear both in the above working-time balance and in the following micro-economic analysis (wage labor during the time saved by the biogas plant).

8.3 Micro-economic Analysis for the User

The following observations regarding micro-economic analysis (static and dynamic) extensively follow the methods and calculating procedures described in the pertinent publication by H. Finck and G. Oelert, a much-used reference work at Deutsche Gesellschaft für Technische Zusammenarbeit

Fig. 8.2: Costs and benefits of a fixed-dome biogas plant (Source: OEKOTOP)

INVESTMENT COSTS

12% Manpower

38% Building materials: blocks, cement, bricks, etc.

14% General engineering

9% Gas appliances

15% Piping

12% Stable modification

OPERATING COSTS

Spare parts

Repair services

BENEFITS

Time for wage labour

Fertilizer yield

Excess energy potential

Savings on energy
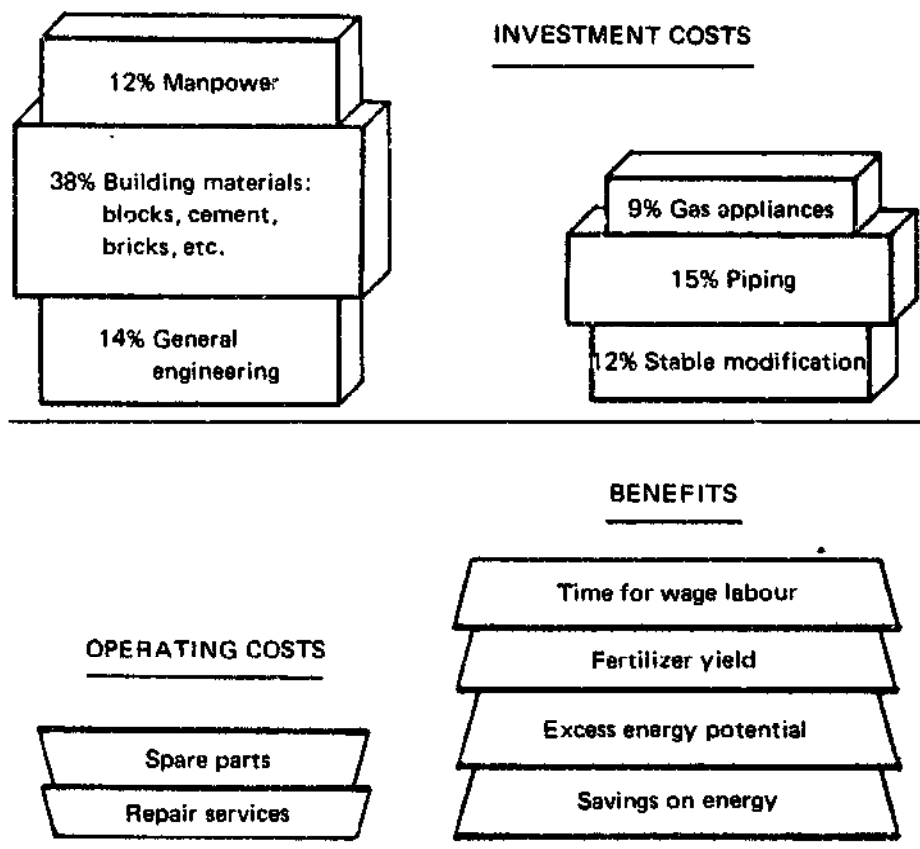
(GTZ) GmbH that should be consulted for details of interest.

Survey of the monetary costs and benefits of a biogas plant

Figure 8.2 shows a breakdown of the basic investment-cost factors for a – presumedly – standardized fixed-dome plant. The cost of material for building the digester, gasholder and displacement pit (cement, bricks, blocks) can, as usual, be expected to constitute the biggest cost item. At the same time, the breakdown shows that the cost of building the plant alone, ·i.e. without including the peripherals (animal housing, gas appliances, piping) does not give a clear picture.

For a family-size plant, the user can expect to pay between 80 and 400 DM per m³ digester volume (cf. table 8.2). This table shows the total-cost shares of various plant components for different types of plant. While the average plant has a service life of 10–15 years, other costs may arise on a recurrent basis, e.g. painting the drum of a floating-drum plant and replacing it after 4–5 years. Otherwise, the operating costs consist mainly of maintenance and repair work needed for the gas piping and gas appliances. At least 3% of the initial investment costs should be assumed for maintenance and repair.

The main benefits of a biogas plant are:
– savings attributable to less (or no) consumption of conventional energy sources for cooking, lighting or cooling
– the excess energy potential, which could be commercially exploited
– substitution of digested slurry in place of chemical fertilizers and/or financially noticeable increases in crop yields
– savings on time that can be used for wage work, for example.

Usually, a biogas plant will only be profitable in terms of money if it yields considerable savings on conventional sources of energy like firewood, kerosene or bottled gas (further assuming that they are not subsidized).

Financially effective crop-yield increases thanks to fertilizing with digested slurry are hard to quantify, i.e. their accurate registration requires intensive observation of the plant's operating parameters.

Such limitations make it clear that many biogas plants are hardly profitable in monetary terms, because the relatively high cost

Table 8.2: Investment-cost comparison for various biogas plants (Source: OEKOTOP)

Cost factor	Water-jacket plant	Fixed-dome plant	Plastic-sheet plant
Cost per m³ digester (DM)	200–400	150–300	80–120
including: Gasholder	23%	(part of digester)	8%
Digester/slurry store	35%	50%	42%
Gas appliances/piping	22%	24%	36%
Stable modification	8%	12%	–
General engineering	12%	14%	14%

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of investment is not offset by adequate financial returns. Nonetheless, if the user considers all of the other (non-monetary) benefits, too, he may well find that operating a biogas plant can be worth his while. The financial evaluation (micro-economic analysis), the essential elements of which are discussed in the following chapter, therefore counts only as one of several decision-making instruments to be presented to the potential user.

The main advisory objective is to assess the user's risk by calculating the payback period ("How long will it take him to get back the money he invested?") and comparing it with the technical service life of the plant. Also, the user must be given some idea of how much interest his capital investment will carry (profitability calculation).

The micro-economic analytical methods described in the following subsections require the highest achievable accuracy with regard to the identification of costs and benefits for the biogas plant under consideration. Chapter 10.4 in the appendix includes an appropriate formsheet for data collection. With a view to better illustrating the described analytical methods, the formsheet (table 10.10) includes fictive, though quite realistic, data concerning a family-size biogas plant. Those data are consistently referred to and included in the mathematical models for each of the various sample analyses.

Calculation of the static payback period according to the cumulative method (data taken from the appendicized formsheet, table 10.10).

Input parameters:
— investment costs
— annual revenues
  — less the yearly operating costs
  — less the external capital costs
  = annual returns

The cumulative method allows consideration of different annual returns.

Calculatory procedure: The investment expenditures and annual returns are added together until the line-3 total in table 8.3 either reaches zero (end of payback period) or becomes positive.

Evaluation: As far as risk minimization is concerned, a short payback period is very valuable from the standpoint of the plant's user ("short" meaning significantly less than 10 years; the data listed in table 8.3 pegs it at 5.5 years). Should the analysis show a payback period of 10 years or more, thus possibly even exceeding the technical service life of the plant, building the plant could not be recommended unless other important factors are found to outweigh that disadvantage.

Table 8.3: Schedule of data for calculating the plant payback period (with case example; data taken from the appendicized formsheet, table 10.10) (Source: OEKOTOP)

Item \ Year	0	1	2	3	4	5	6 etc.
1. Investment expenditures	−1.100						
2. Annual returns		+200	+200	+200	+200	+200	+200
3. Cumulative value	−1.100	−900	−700	−500	−300	−100	+100

Static calculation of profitability
(data taken from table 10.10 in the Appendix)

Input parameters:
- average capital invested per time interval, K_A

$$K_A = \frac{\text{initial investment}}{2} = \frac{Io}{2}$$

- net profit, NP = annual return
  - less the external capital servicing costs
  - less the depreciation

Calculatory procedure: The profitability, or return on investment, ROI, is calculated according to the following formula

$$ROI = \frac{NP}{K_A} \cdot 100$$

The linear annual depreciation amounts to:

$$\frac{Io}{\text{service life}}$$

The technical service life of a biogas plant generally amounts to 10–15 years. It is advisable to calculate twice, one for a pessimistic assumption (10-year service life) and once for an optimistic assumption (15-year service life). Similarly, the net profit should also be varied under pessimistic and optimistic assumptions.

Evaluation: The user can at least expect the biogas plant to yield a positive return on his invested capital. The actual interest should be in the range of locally achievable savings-account interest. Also, the results of profitability calculation can be used to compare the financial quality of two investment alternatives, but only if their respective service lives and investment volumes are sufficiently comparable.

Calculating the profitability using the appendicized data

Initial investment, Io	= 1 100
Average capital invested, $K_A = \frac{Io}{2} = 550$	
Annual returns	= 200
Loan servicing costs	= none (internal financing)
Depreciation for 10-year service life	= 110 (case 1)
Depreciation for 15-year service life	= 73.3 (case 2)
Net profit, NP_1, for case 1	= 90
Net profit, NP_2, for case 2	= 126.7
Return on investment in case 1	= NP_1/K_A = 16%
Return on investment in case 2	= NP_2/K_A = 23%

Thus, this sample calculation can be expected to show positive results regarding the achievable return on invested capital.

8.4 Use of Complex Dynamic Methods

Dynamic methods of micro-economic analysis are applied to biogas plants primarily by:
- extension officers, for the purpose of checking, by a dynamic technique, their own results of static monetary analysis (cf. chapter 8.3), as already explained to the small farmers and other users of biogas plants
- banks, as a decision-making criteria in connection with the granting of loans
- operators of large-scale biogas plants, for whom the financial side of the invest-

Table 8.4: Schedule of data for net-present-value calculation (with case example, data taken from the appendicized formsheet, table 10.10) Source: OEKOTOP)

Item	Period	0 19..	1 19..	2 19..	3 19..	...	10 19..
Investment expenditures		-1.100					
Returns			+200	+200	+200	..	+200
Disocunting factor[1] (for i = 10%)			0.909	0.826	0.751	..	0.386
Present value			+182	+165	+150	..	+77
Cumulative value[2]		-1.100	-918	-753	-603	..	+129

[1] As taken from table 10.11 in the Appendix
[2] Simultaneously enabling dynamic payback calculation

ment is an important factor in the decision-making process.

The importance of the dynamic methods lies in the fact that the results obtained using the simpler static methods of calculation described in chapter 8.3 can become problematic, if the point in time at which payments become due is of increasing imprtance. Any investor naturally will set a lower valuation to revenues that are due a decade from now than to those which are coming in at present. Consequently, he would want to compound past payments and discount future payments to obtain their respective present values.

Net-present-value method

The most commonly employed method of dynamic micro-economic analysis is the net-present-value method used by many extension officers. It enables evaluation of both the absolute and relative advantages of a biogas-plant investment (as compared to other investment alternatives) on the basis of the anticipated minimum interest rate above and beyond the net present value of the investment. Simultaneously, the net-present-value method also serves as a basis for calculating the dynamic payback period

and for calculations based on the annuities method. (For details on the net-present-value and other dynamic methods of calculation, please refer to the aforementioned publication by Finck/Oelert.)

The inflation problem: Either the entire calculation is based on nominal incomes and expenditures, and market interest rates (= calculatory interest) are assumed, or the income and expenditures are presumed to remain constant, and the calculation is based on the real interest rate. The latter is calculated according to the following formulae (p = market rate of interest and a = rate of inflation):

$$i = \frac{100 + p}{100 + a} \cdot 100 - 100$$

Example: market rate of interest = 48%; rate of inflation = 34%

$$i = \frac{100 + 48}{100 + 34} \cdot 100 - 100 = 10.4\%$$

Discounting factors: The compounding and discounting factors for the net-present-value method are shown in table 10.11 (Appendix) for interest rates of 1-30% and service lives of 1-15 years.

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Calculatory procedure: The following information is drawn from the appendicized data survey: calculatory rate of interest, i (item 1.3); investment costs, J (item 2) and the returns (item 8). Much like the static mathematical models discussed in chapter 8.3, the calculatory procedures are again made more readily understandable by inserting the appropriate data from the formsheet (table 10.10, Appendix). In a real case, those data naturally would have to be replaced by the actual on-site data.

Results: The biogas plant can be regarded as profitable, if its net present value is found to be equal to or greater than zero for the minimum acceptable interest rate, e.g. i = 10%. The net present value is arrived at by cumulating the cash-flow value. Among several alternative investments, the one with the highest net present value should be chosen.

Sample calculation: For a plant service life of 10 years (conservative estimate), the cash-flow values reflecting the annual returns times the discounting factor need to be determined and cumulated (cf. table 8.4). In this example, the net present value, at 129, would be positive, i.e. the potential investment would be worthwhile. The effects of discounting future income to its present value are substantial. For example, the return listed as 200 in item 10 would have a cash-flow value of 77 for a calculatory interest rate of 10%.

8.5 Qualitative Evaluation by the User

Biogas plants have numerous direct and indirect advantages — and, under certain circumstances, disadvantages — that cannot be expressed in terms of money, but which can be very important for the user. Even when a biogas plant is not financially profitable, meaning that it costs the user more than it yields, it can still have such a high socio-

Table 8.5: Socioeconomic benefits and drawbacks of biogas production and utilization (Source: OEKOTOP)

Benefits	*Possible drawbacks*
Assured, regular supply of energy rating: + o −	Direct handling of feces rating: + o −
Improved hygienic conditions through better disposal of feces, no smoky cooking fires, less nuisance from flies rating: + o −	Limited communication potential, e.g. no more gathering of wood together rating: + o −
General improvement of the agricultural production conditions, e.g. better livestock hygine/care, improved soil structure rating: + o −	
Upgrading of women's work rating: + o −	
Better lighting rating: + o −	
Higher prestige rating: + o −	

+ applicable	o possibly applicable	− not applicable

economic value as to warrant its installation. Table 8.5 lists the essential socioeconomic biogas-plant evaluation factors, including plus, neutral and minus symbols to allow individual-aspect evaluation.

8.6 Macro-economic Analysis and Evaluation

The main quantifiable macro-economic benefits are:

— national energy savings, primarily in the form of wood and charcoal, with the latter being valued at market prices or at the cost of reforestation

— reduced use of chemical fertilizers produced within the country.

Additionally, foreign currency may be saved due to reduced import of energy and chemical fertilizers.

Macro-economic costs incurred in local currency for the construction and operation of biogas plants include expenditures for wages and building materials, subsidy payments to the plant users, the establishment of biogas extension services, etc. Currency drain ensues due to importing of gas appliances, fittings, gaskets, paints, etc.

In addition to such quantifiable aspects, there are also qualitative socioeconomic factors that gain relevance at the macroeconomic level:

— autonomous decentralized energy supply

— additional demand for craftsmen's products (= more jobs)

— training effects from exposure to biogas technology

— improved health & hygienic conditions, etc.

Considering the present extent of biogas-plant diffusion, such effects should be viewed realistically, i.e. not overvalued. While a substantial number of biogas plants may be installed in one or more regions of a given developing country, they cannot be expected to have much impact at the national level. At the regional and local levels, however, the multipartite effects described in this subsection are definitly noticeable.

9. Social Acceptance and Dissemination

In many cases, the successful commissioning of a few biogas plants generates a keen demand for more plants among local farmers and other interested parties. Consequently, the responsible extension officer often sees himself confronted with the prospect of planning and building more plants. However, before any decision is made in favor of launching a biogas extension program, the extension officer should make an additional detailed analysis of all positive and negative information concerning experience to date with the plants that have already been built. Only if the results so indicate, should he decide to engage in further building and dissemination activities.

9.1 Determining Factors of Acceptance for Biogas Plants

On the whole, the question of acceptance covers all aspects of biogas technology discussed in this book (agriculture, engineering/construction, operation and maintenance, economic viability). In order to avoid redundancy, this chapter is therefore limited to a discussion of general aspects that have not yet been accounted for.

Biogas extension efforts should include special consideration of the role played by women, since it is they and their children who perform much of the important work needed to keep a biogas plant running. This includes tending cattle, collecting substrate, fetching water, operating gas appliances, cooking, spreading digested slurry, etc. In many cultures, however, they are by tradition hardly directly involved in the process of decision making, e.g. the decision "biogas plant: yes/no and how". Nor are they often allowed for in connection with external project planning. In other regions, though, e.g. many parts of West Africa, women are economically independent of their husbands, i.e. they have their own fields, animals and farm-produce marketing channels.

Extension officers charged with planning and building biogas plants often have little or no awareness of the specific local and regional social conventions. Thus, the promotion of participation, the articulation of user interests, and the involvement of local extension workers are all very important for doing them at least some degree of justice.

In general, a general willingness to accept the construction and operation of biogas plants can be expected and/or can be increased by:

Planning/project organization
– involving the users, especially the women, in all decisions concerning "their" biogas plant
– coordinating all essential program measures with target group representatives
– keeping the user/target group informed
– establishing trustworthy, reliable implementing agency;

Sociocultural
– existing willingness to handle feces and gas
– identicality of users (beneficiaries) and operators of the respective biogas plants
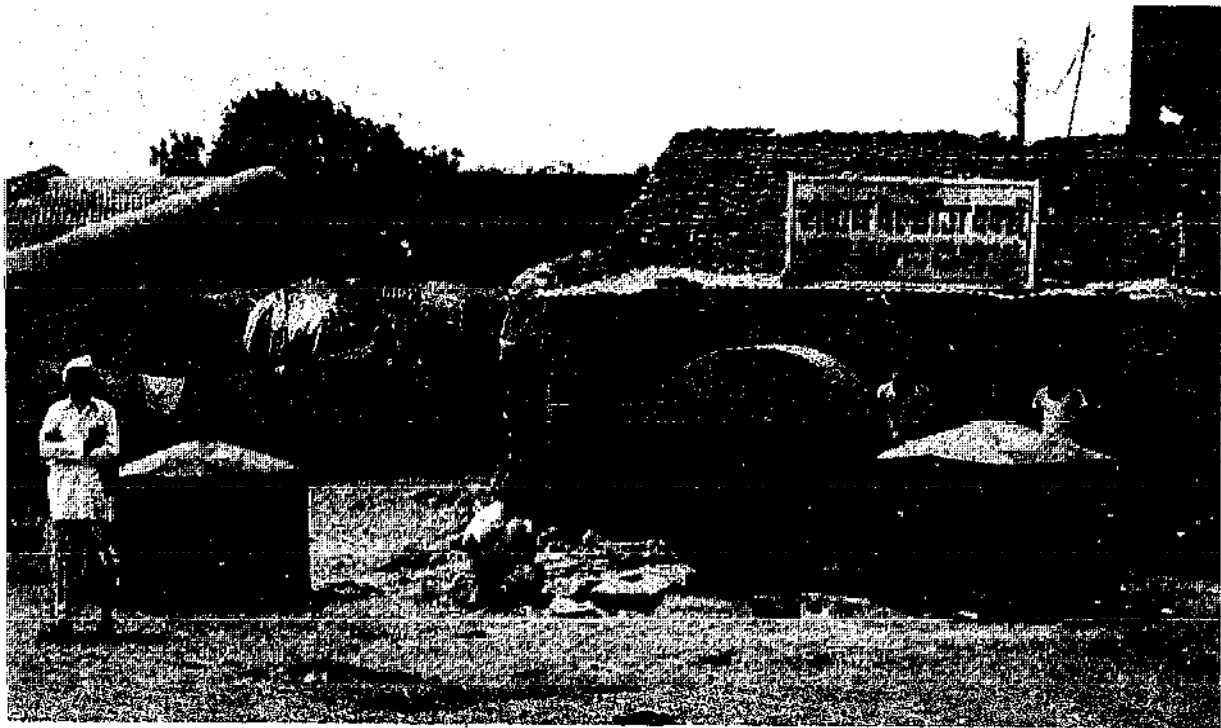– positive image of biogas technology, or image polishing through biogas plants;

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Photo 29: Building metal gasholders in a village workshop in India (Source: Sasse)

Engineering/construction
- well-functioning, durable and good-looking plants from the very start
- availability of well-functioning, inexpensive, modern gas appliances (burners, lamps, refrigerators, etc.)
- user friendliness of plants and appliances
- guaranteed supply of materials and spare parts and assured repair and maintenance;

Agriculture
- stabling practice or tendency toward such practice
- effective time savings, e.g. by direct connection of the biogas plant to the barn
- willingness to use digested slurry as fertilizer, knowledge of storage and spreading techniques, and appreciation of the positive effects of fertilizing
- availability of suitable, inexpensive slurry spreading implements;

Economy
- reasonable expense in terms of money

and work involved (as viewed from the user's standpoint)
- real and, for the user, obviously positive cost-benefit ratio (not necessarily just in terms of money)
- favorable financing (loans, subsidies);

Photo 30: Public-relations effort as part of the Tanzanian Biogas Extension Program (Source: OEKOTOP)

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Coupe d'un digesteur

5. Bassin de stockage
   collecte des déchets
   fermentés.
6. Conduite de gaz.
7. Gazomètre: cloche métallique
   dans un bassin d'eau pour le
   stockage du gaz.
8. Dalle de fondation en béton.

- Volume : 45 m³
- Production de gaz
  par jour 6 m³
- stockage de gaz 5m³
- Matière de ferme-
  ntation: fecès humai-
  nes et déchets
  organiques
- Utilisation du gaz:
  cuisine
- Utilisation des rési-
  dus de fermentation
  fertilisation des rendus

1. Bassin de mélange: mélange des
   déchets avant le remplissage.
2. Tuyau d'entrée des déchets.
3. Digesteur: cuve sphérique avec voûte
   en briques cuites pour la fermentation des déchets.
4. Tuyau de sortie pour les déchets fermentés.

Construit en 1985/P.B. Cunkuza

Photo 31: The Burundi Biogas Extension Program tells about biogas technology (Source: OEKOTOP, BEP Burundi)

Household advantages
— improved working conditions in the kitchen (less smoke and flies, better appearance, modernization)
— introduction or improvement of artificial lighting
— effective workload reduction
— complete, reliable supply of energy through biogas.

It is very important that the biogas extension officer seek intensive contact with the potential plant users and local decision makers in order to maximize the chance of early detection of any deficits regarding the acceptance of biogas technology in order to promptly modify and improve the project strategy as necessary.

Photo 32: A biogas training course in St. Vincent, Caribbean (Source: BEP Caribbean)

9.2 Dissemination Strategies

Ideally, there are two basic strategies for disseminating family-size biogas plants (cf. table 9.1). The original "classic" approach to biogas dissemination – the self-help-oriented approach – has in many regions now taken a backseat to the newer professional-artisan approach. While the "do-it-yourself" approach has the advantage of reaching target groups with relatively little capital and of being applicable in regions with a few or more scattered biogas plants, recent project experience has shown that the professional-artisan strategy leads to a faster and numerically more substantial process of dissemination (once the artisans have been adequately familiarized with the work

involved) and that it does more to promote self-supporting local structures.

Since biogas technology is still regarded as "something new" in most developing regions – even though some pilot plants may already be in operation – the extension officer must very carefully study the regional preconditions for a successful approach to biogas dissemination. This involves getting answers to the following questions:

– What kind of infrastructure does the region have in the way of roads, highways, means of transportation, etc.? The biogas dissemination concept and its timetable must be designed to conform to the given situation.

– How much of the required material is locally available? How much locally un-

Table 9.1: Biogas dissemination strategies (ideal case) (Source: OEKOTOP)

A. Professional-artisan approach	B. Self-help-oriented approach
Dissemination of "turnkey" biogas plants, primarily through professional artisans	Motivated, interested users do part of the construction work
Preconditions:	*Preconditions:*
Adequate capital on the part of the owners/users	Willingness to contribute own efforts (building, maintenance, etc.)
Motivated, qualifiable artisans	User training is highly relevant
High plant density with good income prospects for the artisans	Government or development aid assumes part of the cost for low-income users
Good supply of materials to the artisans, possibly through cooperation between the statal and private sectors; statal sector functions as source of know-how	Well-organized biogas project with adequate presence (despite low plant density) for giving advice, helping to build the plants, and offering technical solutions for a wide diversity of task situations
Measures:	*Measures:*
Offering a complete biogas plant, i.e. a standardized, tested type of plant of a size adequate to the needs of the user, including gas appliances	Offering both standard-type systems and solutions for special problems; reaching out to remote areas
Repair and supply of spare parts by and through local artisans	The project provides the plant elements that can't be built by the users themselves
Qualification of local artisans for planning, building and repairing standardized biogas plants	In addition to local artisans, the users themselves are given training in building, repair and maintenance
Cost reduction through standardization	The project secures locally unavailable materials
	Provision of assistance to the user in the form of subsidies/loans

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Table 9.2: Innovation cycle of biogas dissemination (Source: OEKOTOP)

Regional studies/target groups (ethnological, socioeconomic)
Market analysis (biomass potential, energy demand, purchasing power, market potential, prior state of development, biogas technique, suppliers)
Analysis of implementation (general make-up and organizational structure, finances, personnel qualifications, relation to target group(s)/regional anchorage, political weight)
Formulation of concept
R & D phase, development and adaptation of suitable type of plants to accommodate different areas of service
Installation and operation of pilot plants
Establishment of local partners (artisans, self-help organizations)
Familiarization and training of users, artisans, engineers/planners, advisors, financing institutions, political decision-makers; Media/means: workshops, on-the-job training, handbills, manuals, demonstration models, pictorial material, radio, television
Continuous improvement and sophistication of solutions found (technology, dissemination strategy, organization)

available material can be imported without difficulty? Naturally, as much locally available material as possible should be used for building, maintaining and repairing the plants.

— Are enough adequately qualified and motivated extension workers and craftsmen readily availabe?

— Is there an implementing agency with adequate performance potential and access to the future plant users, thus providing a basis for mutual-thrust cooperation?

Ascertainment of the extent to which the above preconditions are either being met already or could be satisfied through appropriate measures is part of the "biogas innovation cycle" outlined in table 9.2.

9.3 Implementing Agencies

As a rule, biogas programs are implemented by national, state or parastatal institutions. As detailed in chapter 9.4, construction is done by artisans.

In selecting a implementing agency, it is advisable to consider the criteria listed in table 9.3 as a basis for evaluating the qualifications of the implementing agency.

This catalogue can be used to examine existing project partners for real or potential shortcomings with regard to biogas-related task accomplishments with a view to helping them reorganize in order to better handle the job at hand.

Table 9.3: Catalogue of attributes for partners in biogas dissemination projects (Source: OEKOTOP)

Legal form/institutional category (ministry, bank, research institute, rural development institution, etc.)

Work scopes/specialties
– experience with biogas and other renewable energy systems
– experience in rural development

Institutional action principle (break-even operation, maximization of profits, heavy dependence on subsidies)

Managerial organization
– organizational structure (entrenched hierarchy? teamwork? codetermination?)
– classification and institutional significance of the biogas program within the executing organization
– institutional flexibility

Staff endowment for the biogas project
– number and qualifications (special emphasis on agricultural engineers, farmers, technicians, social economists, masons and plumbers, office workers/administrators)
– training offered or possible
– wage and salary structure
– fluctuation, migration

Sundry institutional appointments
– office space, vehicles, telephone, teletex, workshops
– financial endowment of the biogas project (for personnel, transportation, materials and spare parts, public relation activities, etc.)
– potential for providing complementary services in connection with biogas (financing, technical and socio-economic consultancy, maintenance & repair services, etc.)

Interest in the biogas project
– own commercial interest in biogas
– connection with and proximity to the target group and/or to artisans; probability of target group participation
– chances of implementing a national or regional biogas extension program
– domestic importance/prevailing power

9.4 Artisan Involvement

From past experience with inefficient public sponsors and their distance to small-farm target groups, many biogas projects strive to coordinate the activities of private businesses and govermental project organisations through:
– local-scale biogas dissemination work by involving local artisans through personal initiative and customer orientation
– securing the political and organizational framework through regional/supraregional state/parastate sponsors.

The main objective of providing assistance to artisans in connection with biogas projects is to build up self-supporting local structures and promote the formation of regional business cycles with the appropriate effects on technological innovation, employment and income. An efficient form of biogas dissemination, i.e. one based on a good cost/benefit ratio, is envisaged.

Nonetheless, the following points should be heeded when trying to get local artisans involved in the process of biogas dissemination:

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Table 9.4: Institutional breakdown of biogas-dissemination tasks and activities (applies in particular to the professional-artisan approach discussed in chapter 9.2) (Source: OEKOTOP)

Task/Activity	Local artisans	Users	Proj.-executing organization
Biogas-program planning; R&D (appropriate gas applicances and equipment); dissemination strategy concept	participation	participation	responsibility
Individual-plant planning, possibly including the development of standardized plant components	responsibility	participation	responsibility
Provision to users of info and advice	responsibility	–	support
Financing	–	own capital	loans/subsidies
Plant construction:			
– digester excavation	implementation	assistance	planning
– masonry and metalwork	implementation	assistance	planning
– installation of gas pipes and appliances	implementation	assistance	planning
– adaptation of animal housing	implementation	assistance	planning
Procurement of materials and appliances	local materials	–	imported/ rationed goods
Commissioning/operational advice	responsibility; plant-specific	recipients	support; agricultural extension services
Maintenance	support	implementation	–
Repair	implementation	assistance	assistance
Artisan training	recipients	–	implementation
Establishment and development of purchasing and marketing channels for biogas artisans	need promotion	–	responsibility
Establishment of a legal framework, e.g. warranties, liabilities, etc.	–	–	responsibility

— How many qualified craftsmen (masons, welders, plumbers, etc.) are available for work on the project and/or in the villages? To the extent possible, the biogas extension officer should rely on artisans who live and work within the project area.

— How much interest do the artisans have in the project, and how well-motivated are they? What are their expectations regarding income? What is the least number of plants that have to be built in order to guarantee a craftsman a full income or at least a satisfactory sideline income?

— How many and what kind of tools and implements do the artisans have and need? How can the lacking equipment be financed?

Important workscopes for artisans

Depending on the local situation, the artisans' workscopes and competences can vary substantially from place to place. Still, a general breakdown of task scopes can be drawn up for the local craftsmen, the biogas project, the official implementing agency and the user when it comes to planning and operating a biogas plant (cf. table 9.4). The biogas artisans are generally responsible for the following tasks:

— detailed planning of plants for individual sites (presupposing the availability of standardized or modular plant components that are adequate for the situation and can be in-

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stalled with no substantial degree of modification at any suitable site)

— providing advisory services and information to the users

— all work in connection with building and starting the plant, from the digester excavation to the masonry and plumbing — for which the requisite tools and materials must be procured

— any necessary maintenance and repair work.

Both the quality standards for the work to be done and the success of the biogas dissemination efforts are heavily dependent on the presence of qualified craftsmen, particularly masons, in the project region.

9.5 Training

The training measures address different target groups, each with their own specific training contents and methods (cf. table 9.5):

— the engineers and extension officers, who are to do the planning and assume advisory duties

— the artisans, who are to build the plants and keep them in repair

— the owners, who require qualification for operating the plants efficiently and, possibly, know-how for performing at least some of the building, maintenance and repair work on their own.

The following items require consideration in connection with biogas training measures:

Table 9.5: Target-group-oriented biogas training measures (Source: OEKOTOP)

Target group	Training elements	Contents	Duration	Instructor
Engineers, local extension officers	Seminars and field trips, national workshops, supraregional conferences serving to effect technology transfer	Function of various types of biogas plants and peripheral equipment, use of digested slurry, maintenance and repair problems, macro- and microeconomic analysis/evaluation, project management	several blocks of approx. 1 week each	biogas experts, agricultural experts, social economists
Artisans	Integrated workshops with theoretical + practical training, incl. on-the-job training (OJT)	Function of selected types of plants, design and construction per drawing, use of local materials, maintenance & repair	workshops lasting several days, participation in plant construction	engineers, experienced artisans
Users	Field trips to operable plants, participation in workshops On-the-spot traini (own plant)	Function of selected types of plants, operation and optimal use, fertilizing with digested slurry, maintenance & repair	2–3 days, regular on-site backstopping	local biogas/ agricultural extension workers
Women	On-the-spot training (own plant), local evening courses	Plant function, operation and optimal use, working with biogas cookers	continuous familiarization	local biogas extension workers (women!)

— Training courses and training material must be held/written in the national or regional language.

— The training material must correspond to the specific targetgroup situation, e.g. experience has been good with loose-leaf material that can be compiled and revised as necessary to fit the needs of each particular target group.

— The demonstration models must agree with the types of plant actually proposed, i.e. do not dry to explain the abstract principle of an oil-drum model or put a fixed-dome on display, when floating-drum plants are supposed to be installed.

— A great deal of practical training must be provided. Positive experience has been made with integrated workshops in which theoretical training is combined with hands-on experience in the construction of a real plant.

— Women must be included in the training measures.

Supraregional workshops, even going beyond the country's borders (allowing the exchange of experience from country to country) are a worthwhile training device for engineers, extension officers and, to some extent, artisans. Training/attendance certificates are recommended as a means of developing training standards and motivating trainees to participate in the courses offered.

9.6 Financing

Small farmers in particular rarely have the DM 1000–2500 or more it takes to cover the cost of a biogas plant. Consequently, "mixed-financing models" with the three elements own capital/contribution, subsidy and loan must be available.

Own capital/contribution

While a potential user may not be able to fully finance a biogas plant by himself, he

must be expected to carry at least 30–40% of the initial outlay, possibly in the form of contributed work like digester excavation, procuring building materials, etc.

Subsidies

The economic benefits of a biogas plant can be quite modest, e.g. when it serves as a substitute for wood that can be gathered for free. The overall benefits, however, including such environmental factors as the protection of forests, can be very substantial. Consequently, the user of the plant should be eligible for subsidies to make up the difference. Such subsidies may consist of:

— contributions to the cost of construction in the form of needed materials (metal gasholder, cement, fittings, etc.), such frequently scarce goods and materials also including those needed for repairs and replacements, e.g. rustproofing for the gasholder,

— free planning and consulting

— assumption of interest debt on loans.

On the whole, however, subsidies have the following drawbacks:

— Market prices can become distorted, and needed capital can be falsely invested.

— Subsidies intended explicitly for the needy may end up in the hands of well-to-do groups.

In addition, prior project experience has shown that user motivation is frequently lower in the case of heavily subsidized plants than in the case of plants that have been evaluated and built on a commercial basis.

Loans

The monetary returns from a biogas plant, particularly those from a small family-size one, are often meagre in comparison to the cost of investment. In other words, the plant hardly pays for itself in terms of real income. Additionally, since most small farmers have no access to commercial loans,

but should not be expected to accept an excessive risk of indebtedness, it can be quite difficult to arrange biogas-plant credit financing for that group of users. The following conditional factors therefore should be investigated prior to setting up any particular credit program:

– first, check out all other funding alternatives, e.g. owned capital;

– then, conduct a detailed socioeconomic analysis of the target group and farms, e.g. which farm can afford how much debt burden?;

– next, clarify the institutional tie-in, i.e. involvement of rural development banks or credit unions;

– and, lastly, establish the program quality, e.g. isolated or integrated credit programs, the latter including technical and economic extension services, training, plant maintenance and repair.

If the appraisal shows that there is available within the region a credit program that is open to the financing of biogas plants and would offer favorable conditions, e.g. a soft-loan program, then the biogas program should rely on it. Establishing an independent credit program without the assistance of an experienced institution is usually so complicated as to overtax an individual project.

A pragmatic loan-tendering model could be designed along the following lines:

– Development-aid funds are put in a time-deposit account at a rural development bank. The bank agrees to provide loans amounting to several times the deposited amount for the purpose of financing biogas plants.

– The loans are not given directly to the beneficiary (plant owners), but channeled through a biogas extension office.

– The office does not issue the loans in cash, but in the form of materials (cement, metal gasholders, etc.).

– The material is issued on the basis of construction progress.

– Repayment of the loans is supervised by the biogas extension office with the assistance of the aforementioned rural development bank.

– A loan guarantee fund into which, say, 10% of each granted loan is fed helps out in case of loan arrears.

This model involves the following risks:

– The biogas extension office may be overburdened by the task of investigating creditability, granting loans and helping to monitor repayment of the loans.

– The guarantee fund could dry up due to default on the part of the beneficiaries, or because the loans were not properly calculated on a break-even basis (inflation, inadequate interest).

Such problems can be overcome in the medium-to-long term by establishing credit unions. That process, though, demands lots of experience and can normally be expected to by far surpass the project terms. Credit unions backed by the plant owners could gradually replace the development-aid part of the lending program. Also, the credit unions could assume responsibility for the aforementioned loan guarantee fund, thus gaining a say in the control of repayment. In most cases, that would improve the lending program's reflux quota while helping to establish rural self-help organizations – a goal that should be viewed as an implicit element of any biogas program.

10. Appendix

10.1 Design Calculations and Drawings

10.1.1 Floating-drum plants

Design calculation

Sizing factors	*Example*
Daily substrate input, Sd	= 115 l/d
Retention time, RT	= 70 days
Daily gas production, G	= 2.5 m³/d
Storage capacity, Cs	= 60%
Digester volume, Vd	= 8 m³
Gasholder volume, Vg	= 1.9 m³

Calculating formulae after Sasse, 1984

1. $Vg = Cs \cdot G$
2. hg = design-dependent
3. $Vg = r \pi \cdot h$
4. $rg = \sqrt{Vg/(\pi \cdot h)}$
5. $rd = r + 0.03$
6. $Vd1 = \pi \cdot d^2 \cdot \pi \cdot h$
7. $Vd2 = R^3 \cdot \pi \cdot 2/3$
8. $R = \sqrt[3]{Vd2/(\pi \cdot 2/3)}$
9. $Vd3 = R^2 \cdot \pi \cdot H/3$
10. $H = R/5$
11. $Vd3 = R^3 \cdot \pi \cdot 1/15$
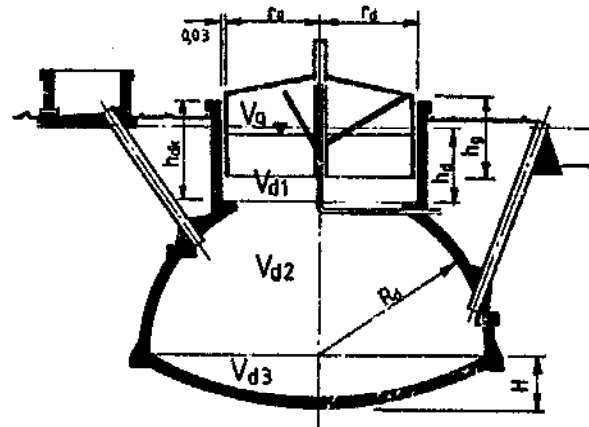
Fig. 10.1: Conceptual drawing of a floating-drum biogas plant

$V_d = V_{d1} + V_{d2} + V_{d3}$
= digester volume
V_g = gasholder volume
Index g = gas holder
Index d = digester

12. $Vd2 : Vd3 = 10 : 1$
13. $Vd(2+3) = 1.1 Vd2$
14. $Vd(2 + 3) = Vd - Vd1$
15. $hd = hg$
16. $hdk = hd$ + structurally dependent free board (0.1 . . . 0.2 m)

Sample calculation				*Results*
1.	Vg	= 0.6 · 2.5		= 1.5 m³
	hg	= (specified)		= 0.7 m
4.	r	= $\sqrt{1.5/3.14 \cdot 0.7}$		= 0.82 m
5.	r	= 0.85 (chosen)		
6.	Vd1	= $0.85^2 \cdot 3.14 \cdot 0.7$		= 1.58 m³
14.	Vd (2 + 3)	= 8.45 − 1.58		= 6.87 m³
8 + 14.	R	= $\sqrt[3]{6.87/(1.1 \cdot 3.14 \cdot 2/3)}$		= 1.45 m
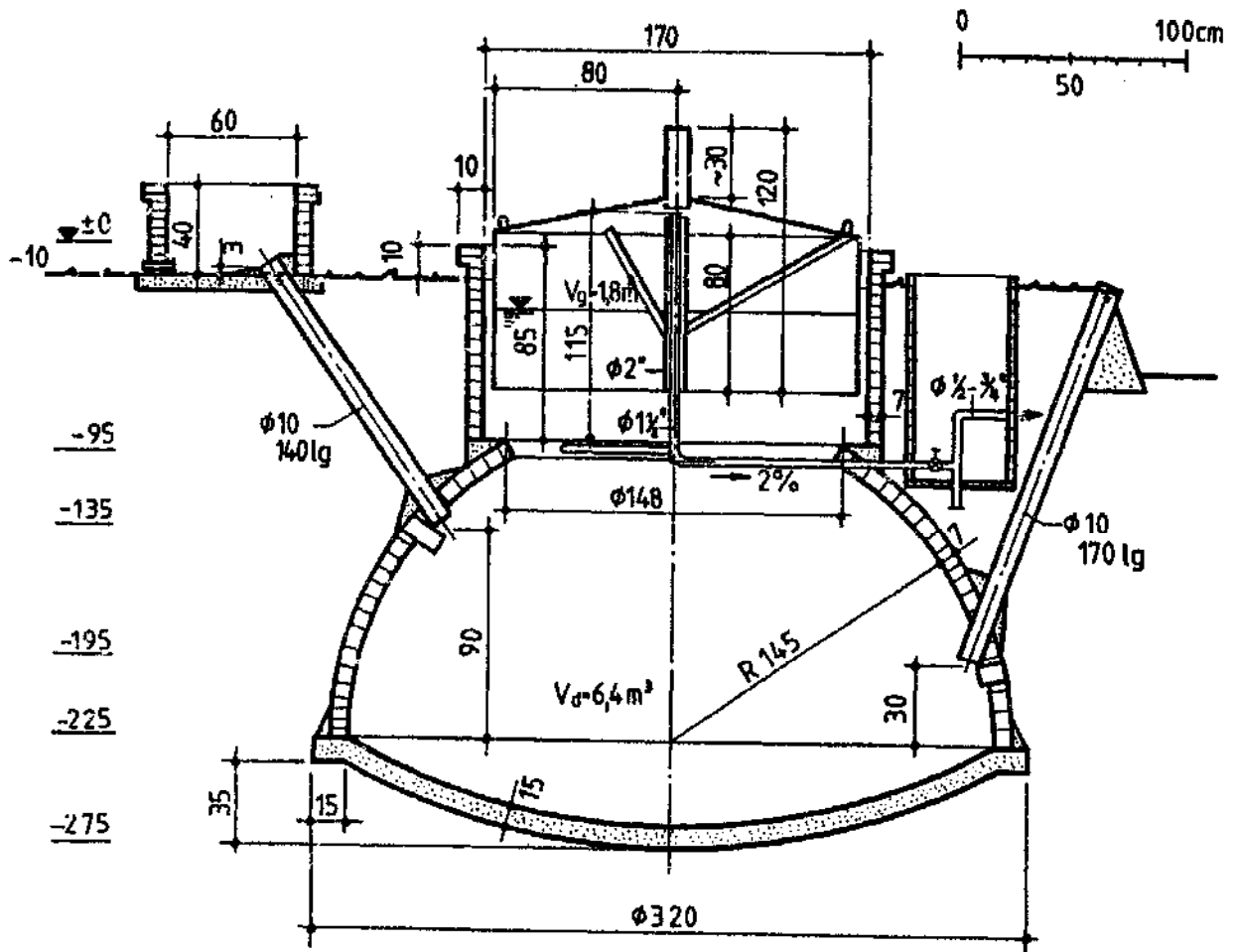
Fig. 10.2: Constructional drawing of a floating-drum plant. V_d = 6.4 m³, V_g = 1.8 m³. Material requirements: Excavation 16.0 m³, Foundation 1.6 m³, Masonry 1.1 m³, Rendered area 18.0 m², Sheet steel 5.7 m². (Source: OEKOTOP, Sasse)

Fig. 10.3: Constructional drawing of a water-jacket plant. V_d = 6.0 m³, V_g = 1.8 m³. Material requirements: Excavation 16.0 m³, Foundation 1.6 m³, Masonry 1.6 m³, Rendered area 21 m², Sheet steel 5.7 m². (Source: OEKOTOP, Sasse)
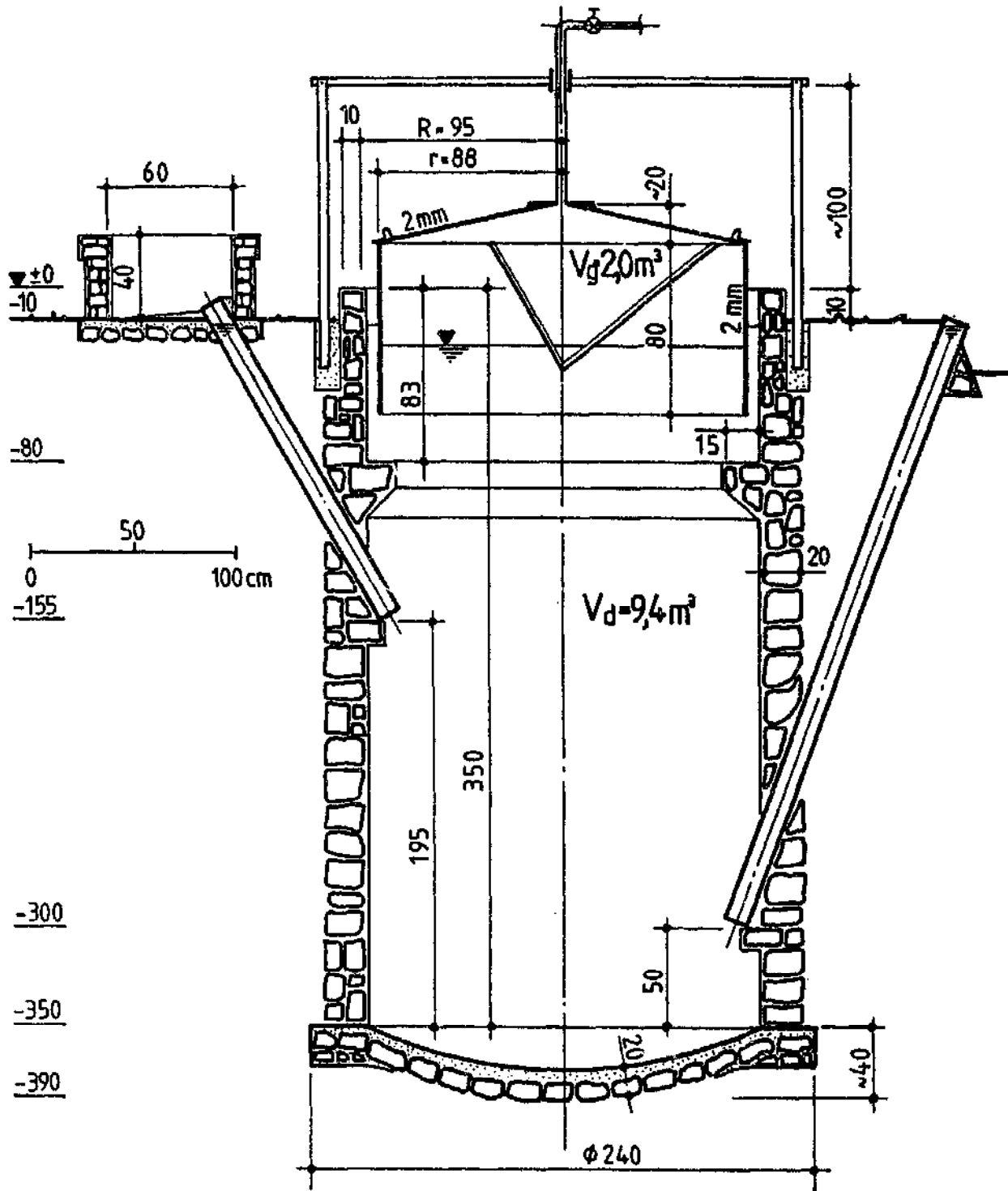
Fig. 10.4: Constructional drawing of a cylindrical floating-drum plant for quarrystone masonry. $V_d =$ 9.4 m^3, $V_g =$ 2.5 m^3. Material requirements: Excavation 21.0 m^3, Foundation 1.0 m^3, Masonry 5.4 m^3, Rendered area 27.3 m^2, Sheet steel 6.4 m^2. (Source: OEKOTOP, KVIC)

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10.1.2 Fixed-dome plants

Design calculation

Sizing factors	Example	Sample calculation
Daily substrate input, Sd	= 115 l/d	
Retention time, RT	= 70 days	$R = \sqrt[3]{0.76 \cdot 8}$ = 1.85 m
Daily gas production, G	= 2.5 m³/d	r = 0.52 R = 0.96 m
Storage capacity, Cs	= 60%	h = 0.40 R = 0.72 m
Digester volume, Vd	= 8 m³	p = 0.62 R = 1.14 m
Gasholder volume, Vg = G · Cs	= 1.5 m³	
Vd : Vg	= 5.3 : 1	

Tab. 10.1: Calculating parameters for fixed-dome biogas plants (Source: Sasse 1984/OEKOTOP)

Vg : Vd	1 : 5	1 : 6	1 : 8
R	$\sqrt[3]{0,76\ Vd}$	$\sqrt[3]{0,74\ Vd}$	$\sqrt[3]{0,72\ Vd}$
r	0,52 R	0,49 R	0,45 R
h	0,40 R	0,37 R	0,32 R
p	0,62 R	0,59 R	0,50 R
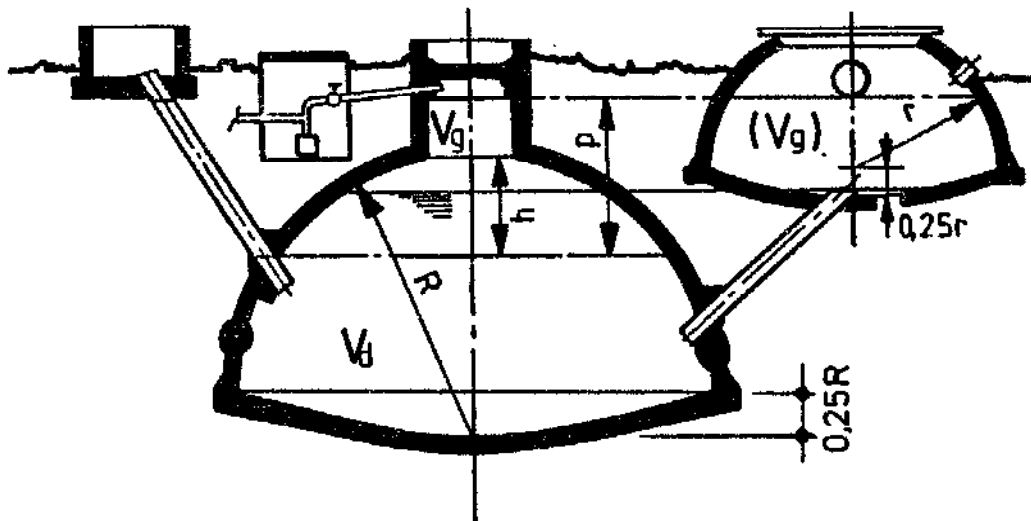
Fig. 10.5: Conceptual drawing of fixed-dome biogas plant. V_g gasholder volume, V_d digester volume. (Source: OEKOTOP, Sasse)

Fig. 10.6: Constructional drawing of a fixed-dome plant. V_d = 8 m³, V_g = 1.5 m³. Material requirements: Excavation 25 m³, Foundation 2.2 m³, Masonry 2.0 m³, Rendered area 22.0 m², Sealed area 7.0 m². (Source: ÖEKOTOP, Sasse, BEP Tanzania)

10.1.3 Earth pit with plastic-sheet gasholder
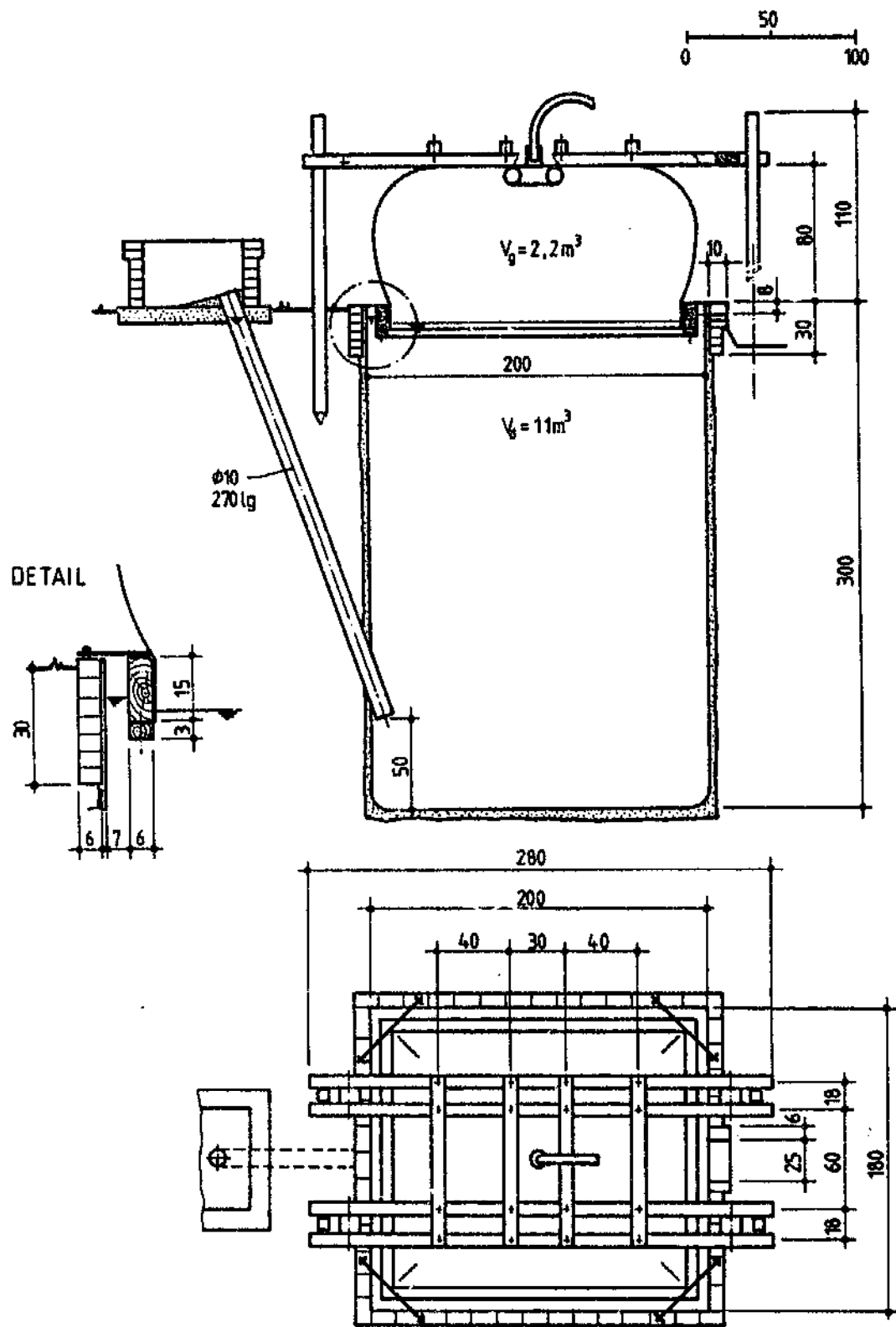
Fig. 10.7: Constructional drawing of an earth-pit biogas plant with plastic-sheet gasholder. $V_d = 11$ m^3, $V_g = 2.2$ m^3. Material requirements: Excavation 16 m^3, Rendered area 28 m^2, Sheeted area 10 m^2. (Source: OEKOTOP)

10.1.4 Estimating the earth-pressure and hydraulic forces
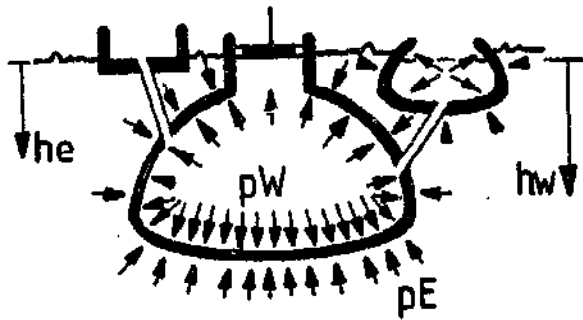
Fig. 10.8: Schematic diagram of earth-pressure and water-pressure forces

In-depth forces, h (e, w)

$$pW = wW \cdot hw$$

pW = hydrostatic pressure at depth hw (m)
wW = specific weight of water
= 1 000 kp/m³

$$pW = 1\,000 \cdot h \; (kp/m^2)$$

$$pE = wE \cdot ce \cdot he$$

pE = active earth pressure, i.e. force of pressure of dry, previously loose but now compact column of earth on a solid vertical wall
wE = specific weight of dry backfill earth
= 1 800 ... 2 100 kp/m³
he = height of earth column (m)
ce = coefficient of earth pressure for the earth column in question
= 0.3 ... 0.4 (−)

$$pE = (600 \ldots 700) \cdot h \; (kp/m^2)$$

Force acting on a surface

$$P(E, W) = p \cdot A \; (kp = (kp/m^2) \cdot m^2)$$

Note: The above formulae are simplified and intended only for purposes of rough estimation.

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10.2 Gas-law Calculations

10.2.1 Calculating the pressure drop in a gas pipe

$$dp = FL + Ztot$$

dp = pressure drop (N/m^2)
FL = friction losses in the gas pipe (N/m^2)
Ztot = sum total of friction losses from valves, fittings, etc. (N/m^2)

$$dp = cp \cdot l/D \cdot D/2 \cdot v^2$$
$$+ (cf1 \cdot D/2 \cdot v^2 + \ldots + cfn \cdot D/2 \cdot v^2)$$
(approximation formula)

cp = coefficient of pipe friction (−)
l = length of pipe section (m)
D = pipe diameter (m)
g = density of biogas (1.2 kg/m³)
v = velocity of gas in the pipe (m/s)
cf = friction coefficients of valve, fittings, etc.

$$Q = v \cdot A$$

Q = gas flow (m^3/s)
v = velocity of gas in the pipe (m/s)
A = πr^2 = cross-sectional area of pipe

The *coefficient of pipe friction* (cp = nondimensional) is a function of:
− the pipe material and internal surface roughness
− pipe diamter
− flow parameter (Reynolds number)

For pipe diameters in the $1/2'' \ldots 1''$ range, the coefficients of friction read:
PVC tubes   approx. 0.03
steel pipes   approx. 0.04

Some *individual friction-loss factors (cf; nondimensional)*

elbow	0.5	valve	3.0
constriction	0.02−0.1	water trap	3−5
branch	0.8−2.0		

10.2.2 Calculating gas parameters

Temperature-dependent change of volume and density

$$D = DN \cdot \frac{P \cdot TN}{PN \cdot T}$$

$$V = VN \cdot \frac{PN \cdot T}{P \cdot TN}$$

where:

D = density of biogas (g/l)

DN = density under s.t.p. conditions (0 °C, 1013 mbar)

V = volume of biogas (m^3)

VN = volume of biogas under s.t.p. conditions

P = absolute pressure of biogas (mbar)

PN = pressure under s.t.p. conditions (1013 mbar)

T = absolute temperature of biogas (measured in °Kelvin = °C + 273)

TN = temperature under s.t.p. conditions (0 °C = 273 °K)

Table 10.2: Atmospheric pressure as a function of elevation (Source: Recknagel/Sprenger, 1982)

Elevation (km)	0	0.5	1.0	2	3	4	6	8
Atm.pressure (mbar)	1013	955	899	795	701	616	472	365

Fig. 10.9: Nomogram for correcting gas pressures/temperatures (Source: OEKOTOP)

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7 Hu,N (kWh/m³)
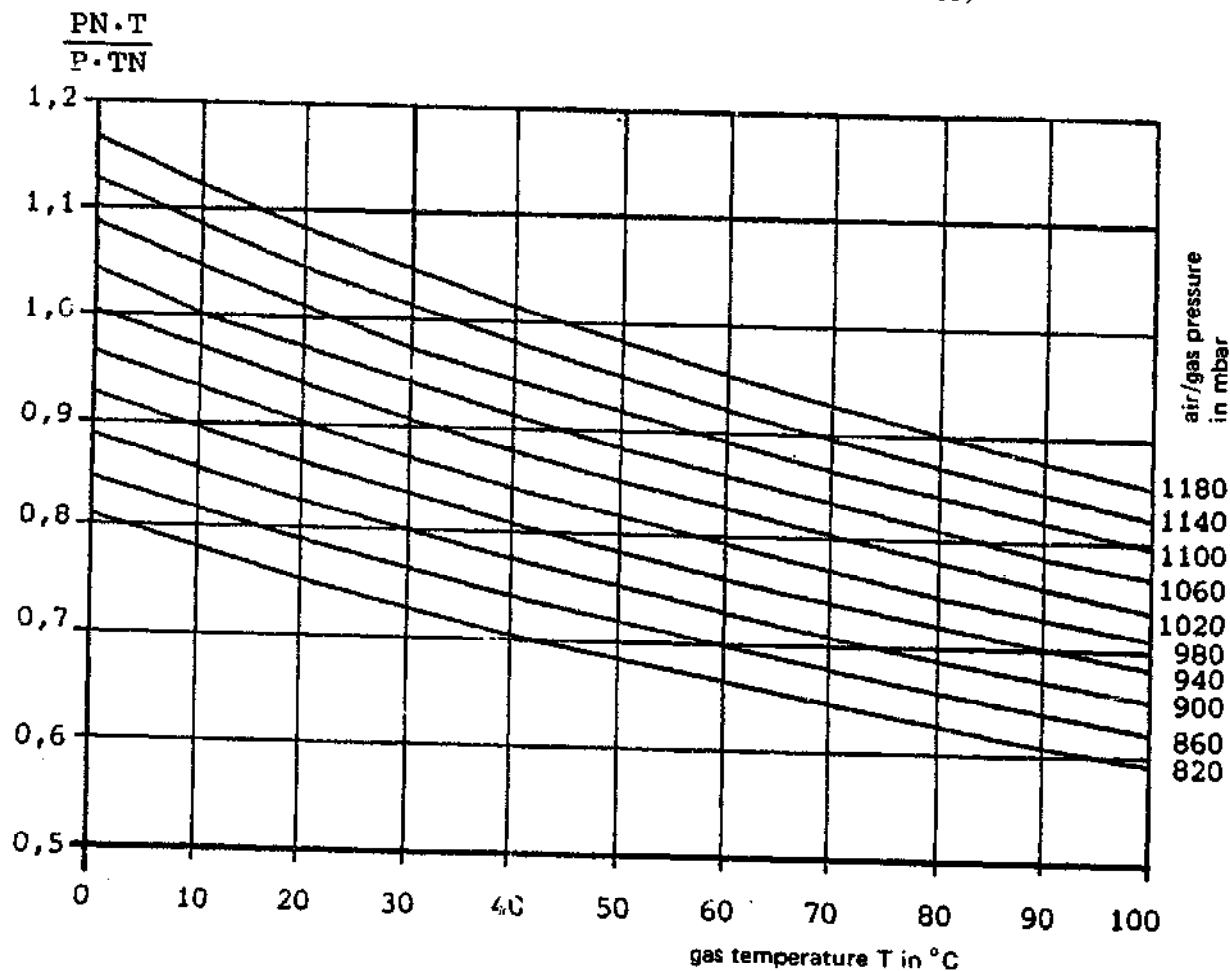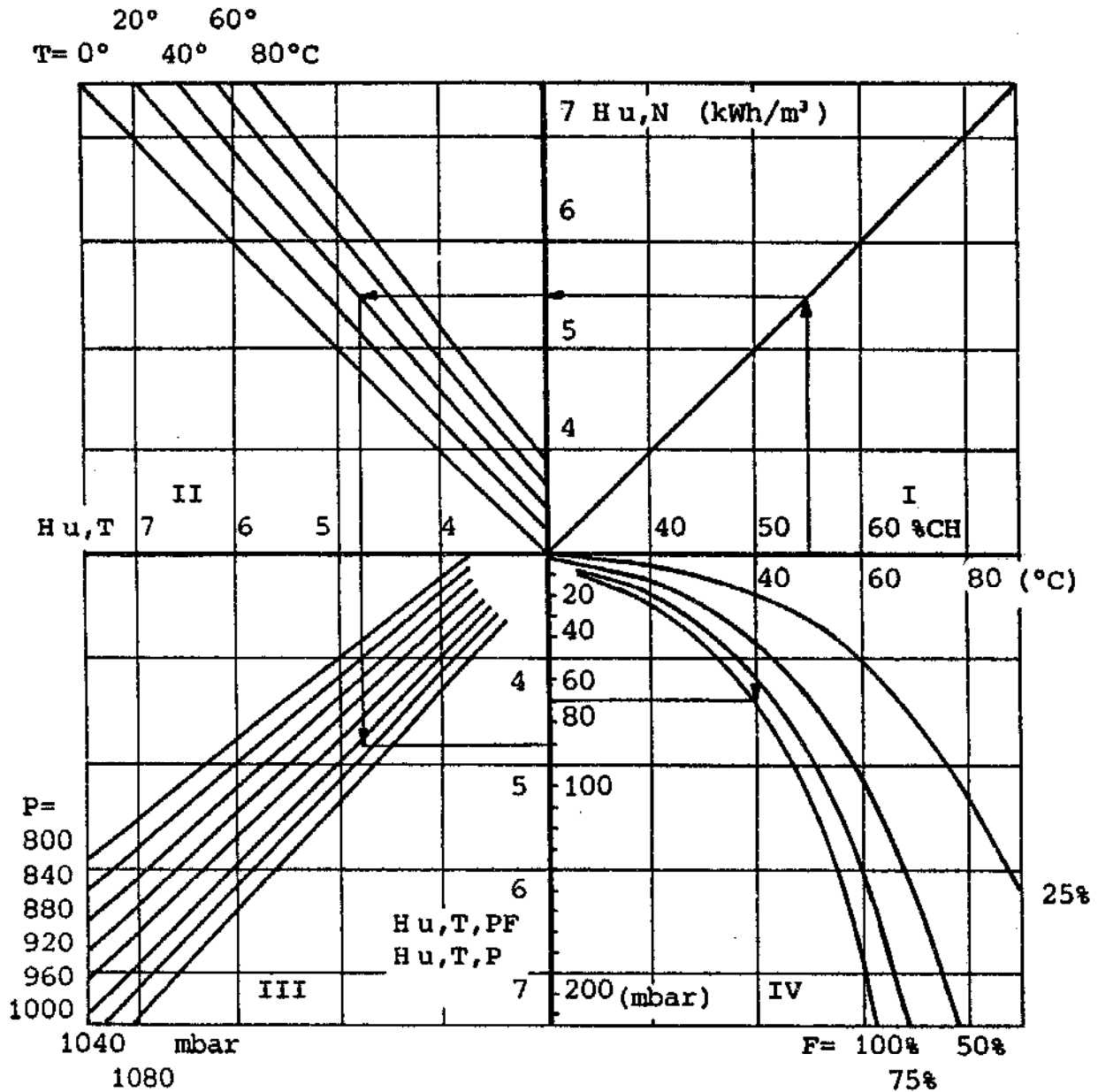
Fig. 10.10: Nomogram for finding the net calorific value of biogas as a function of temperature, pressure and moisture content. T gas temperature (°C), F relative dampness of biogas (%), Hu, N net calorific value (n.c.v.) of biogas under s.t.p. conditions (0 °C, 1013 mbar), Hu, T net calorific value (n.c.v.) at gas temperature, P gas pressure (mbar), Hu, T, P net calorific value (n.c.v.) at gas temperature and pressure, PW partial pressure of water vapor, Hu, T, PF net calorific value (n.c.v.) of biogas at gas temperature, corrected to reflect the water-vapor fraction (Source: OEKOTOP)

Using the nomogram

1. Quadrant I: Determine the net calorific value under standard conditions as a function of the CH₄-fraction of the biogas
2. Quadrant II: Determine the net calorific value for a given gas temperature
3. Quadrant III: Determine the net calorific value as a function of absolute gas pressure (P)

4. Quadrant IV: Interim calculation for determining the partial water-vapor pressure as a function of gas temperature and relative dampness. This yields the gas pressure (PF) = absolute pressure (P) − partial pressure of water vapor (PW); PF = P − PW. The expanded calorific value determination with account for the moisture content occurs via quadrant III.

Sample calculation

Given:

Biogas	55 vol. % CH_4
Gas temperature	T = 40 °C
Gas dampness	F = 100%
Gas pressure	P = 1030 mbar

Results:

Hu, N	= $f(CH_4$-vol. %)	Quadrant I
	= 5.5 kWh/m³	
Hu, T	= f(T)	Quadrant II
	= 4.8 kWh/m³	
Hu, T, P	= f(T, P)	Quadrant III
	= 4.6 kWh/m³	
PF	= f(P, T)	Quadrant IV
	− f(PW)	Quadrant III
Hu, T, PF	= 4.3 kWh/m³	

Table 10.3: Partial pressure of water vapor, PW, and absolute humidity, GM, at the saturation point (Source: Recknagel/Sprenger, 1982)

T (°C)	PW (mbar)	GM (g/m³)
0	6.1	4.9
10	12.3	9.4
20	23.4	17.3
30	42.4	30.4
40	73.7	51.2
50	123.3	33.0
60	199.2	130.2
70	311.6	198.2
80	473.6	293.3
90	701.1	423.5
100	1013.3	597.7

10.3 Conversion Tables

Table 10.4: SI units of calculation (selection) (Source: OEKOTOP, compiled from various sources)

Quantity	Symbol	Unit	Conversion
Length	l	m	1 m = 10 dm = 100 cm = 1000 mm
Area	A	m²	1 m² = 100 dm² = 10000 cm²
Volume	V	m³	1 m³ = 1000 dm³ = 1 mill. cm³
Mass	M	t; kg	1 t = 1000 kg
Density	D	t/m³	1 t/m³ = 1 kg/dm³
Force, load	F	kN	1 kN = 1000 N ~100 kp
Stress	δ	MN/m²	1 MN/m² = 1 N/mm² ~10 kp/cm²
Pressure	P	MN/m²	1 MN/m² = 1 MPa ~10 kp/cm²
Energy	E	kWh	1 kWh = 3.6 · 10⁶ Ws ~3.6 · 10⁵ kpm
Work	W	kNm	1 J = 1 Ws = 1 Nm; 1 kNm ~ 100 kpm
Quantity of heat	Q	kWh	1 kWh = 3.6 × 10⁶ Ws; 1 kcal = 4187 Ws
Power	P	kW	1 kW ~100 kpm/s = 1.36 PS
Temperature	t	°C, K	0 °K = −273 °C; 0 °C = 273 °K
Velocity	v	m/s	1 m/s = 3.6 km/h
Acceleration	b	m/s	1 m/s², acceleration due to gravity: 9.81 m/s²

Table 10.5: Conversion of imperial measures (Source: Sasse, 1984)

Length	1 m = 1.094 yrd	1 yrd = 0.914 m
	1 cm = 0.0328 ft	1 ft = 30.5 cm
	1 cm = 0.394 inch	1 inch = 2.54 cm
Area	1 m^2 = 10.76 sqft	1 sqft = 0.092 m^2
	1 cm^2 = 0.155 sq.in	1 sq.in = 6.452 cm^2
	1 ha = 2.47 acre	1 acre = 0.405 ha
Volume	1 l = 0.220 gall.	1 gall. = 4.55 l
	1 m^3 = 35.32 cbft	1 cbft = 28.31
Mass	1 kg = 2.205 lb	1 lb = 0.454 kg
Pressure	1 MN/m^2 = 2.05 lb/sqft	1 lb/sqft = 0.488 MN/m^2
	1 cm Ws = 205 lb/sqft	1 lb/sqft = 70.3 cm Ws
Quantity of heat	1 kcal = 3.969 BTU	1 BTU = 0.252 kcal
	1 kWh = 3413.3 BTU	1000 BTU = 0.293 kcal
	1 kcal/kg = 1799 BTU/lb	1 BTU/lb = 0.556 kcal/kg
Power	1 PS = 0.986 HP	1 HP = 1.014 PS
	1 kpm/s = 7.24 ft.lb/s	1 ft.lb/s = 0.138 kpm/s

Table 10.6: Conversion factors for work, energy and power (Source: Wendehorst, 1978)

Comparison of work units (work = power X time)

	kpm	PSh*	Ws = J	kWh	kcal
1 kpm =	1	3.70×10^{-6}	9.807	2.7×10^{-6}	2.342×10^{-3}
1 PSh* =	270×10^3	1	2.648×10^6	0.7355	632.4
1 Ws = J =	0.102	377.7×10^{-9}	1	277.8×10^{-9}	239×10^{-6}
1 kWh =	367.1×10^3	1.36	3.6×10^6	1	860
1 kcal =	426.9	1.58×10^{-3}	4186.8	1.163×10^{-3}	1

* PS = 0.986 HP

Table 10.7: Energy content of various fuels (Source: Kaltwasser, 1980)

Fuel	Calorific value MJ	kWh	Unit
Plants	16–19	4.4– 5.3	kg TS
Cow dung	18–19	5.0– 5.3	kg TS
Chicken droppings	14–16	3.9– 4.4	kg TS
Diesel, fuel oil, gasoline	41–45	11.4–12.5	kg = 1.1 l
Hard coal (anthracite)	30–33	8.3– 9.2	kg
Wood	14–19	3.9– 5.3	kg
Producer gas	5– 7	1.4– 1.9	Nm^3
Pyrolysis gas	18–20	5.0– 5.6	Nm^3
City gas	18–20	5.0– 5.6	Nm^3
Propane	93	25.8	Nm^3
Natural gas	33–38	9.2–10.6	Nm^3
Methane	36	10.0	Nm^3
Biogas	20–25	5.6– 6.9	Nm^3

Table 10.8: Conversion factors for units of pressure (Source: Wendehorst, 1978)

	kp/m²	N/m²	pa	cm WG	mbar	at
kp/m²	1	10	10	0.1	0.1	0.0001
N/m²	0.1	1	1	0.01	0.01	10^{-5}
pa	0.1	1	1	0.01	0.01	10^{-5}
cm WG	10	100	100	1	1	0.001
mbar	10	100	100	1	1	0.001
at	10^4	10^5	1000	1000	1000	1

Table 10.9: Table of powers and radicals

n	n^2	n^3	n	n^2	n^3	n	n^2	n^3	n	n^2	n^3
0.60	0.36	0.22	1.10	1.21	1.33	1.60	2.56	4.10	2.10	4.41	9.26
0.65	0.42	0.27	1.15	1.32	1.53	1.65	2.72	4.49	2.15	4.62	9.94
0.70	0.49	0.34	1.20	1.44	1.73	1.70	2.89	4.91	2.20	4.84	10.65
0.75	0.56	0.42	1.25	1.56	1.95	1.75	3.06	5.36	2.25	5.06	11.39
0.80	0.64	0.51	1.30	1.69	2.20	1.80	3.24	5.83	2.30	5.29	12.17
0.85	0.72	0.61	1.35	1.82	2.46	1.85	3.42	6.33	2.35	5.52	12.98
0.90	0.81	0.73	1.40	1.96	2.74	1.90	3.61	6.86	2.40	5.76	13.82
0.95	0.90	0.86	1.45	2.10	3.05	1.95	3.80	7.41	2.45	6.00	14.71
1.00	1.00	1.00	1.50	2.25	3.38	2.00	4.00	8.00	2.50	6.25	15.63
1.05	1.10	1.16	1.55	2.40	3.72	2.05	4.20	8.62	2.55	6.50	16.58

n	$\sqrt[3]{n}$	n	$\sqrt[3]{n}$	n	$\sqrt[3]{n}$	n	$\sqrt[3]{n}$	n	$\sqrt[3]{n}$	n	$\sqrt[3]{n}$
0.001	0.10	0.22	0.60	1.33	1.10	4.10	1.60	9.26	2.10	17.58	2.60
0.003	0.15	0.27	0.65	1.53	1.15	4.49	1.65	9.94	2.15	18.61	2.65
0.008	0.20	0.34	0.70	1.73	1.20	4.91	1.70	10.65	2.20	19.68	2.70
0.016	0.25	0.42	0.75	1.95	1.25	5.36	1.75	11.39	2.25	20.80	2.75
0.027	0.30	0.51	0.80	2.20	1.30	5.83	1.80	12.17	2.30	21.95	2.80
0.043	0.35	0.61	0.85	2.46	1.35	6.33	1.85	12.98	2.35	23.15	2.85
0.064	0.40	0.73	0.90	2.74	1.40	6.86	1.90	13.82	2.40	24.39	2.90
0.091	0.45	0.86	0.95	3.05	1.45	7.41	1.95	14.71	2.45	25.67	2.95
0.125	0.50	1.00	1.00	3.38	1.50	8.00	2.00	15.63	2.50	27.0	3.00
0.166	0.55	1.16	1.05	3.72	1.55	8.62	2.05	16.58	2.55	28.37	3.05

$$F = a^2$$

$$F = a \cdot b$$

$$F = \frac{a+c}{2} \cdot h$$

$$F = \frac{a \cdot h}{2}$$

$$F = \pi \cdot r^2$$
$$U = 2r \cdot \pi$$

$$F = \frac{\pi \cdot r^2}{2}$$
$$U = r \cdot \pi$$

$$F = \pi(r+R) \cdot a$$
$$F = \left(r+\frac{a}{2}\right) \cdot 2\pi \cdot a$$

$$F = \frac{\pi \cdot r^2 \cdot \alpha°}{360°}$$

$$V = a^3$$

$$V = a \cdot b \cdot c$$

$$V = \frac{h}{3} \cdot (F+f+ \sqrt{F \cdot f})$$
$$V \sim (a \cdot b + c \cdot d) \cdot \frac{h}{2}$$

$$V = a \cdot b \cdot \frac{h}{3}$$

$$V = \frac{4}{3}\pi \cdot r^3$$
$$Q = 4\pi \cdot r^2$$

$$V = \frac{2}{3}\pi \cdot r^3$$
$$Q = 2\pi \cdot r^2$$

$$V = \pi \cdot h^2 \cdot \left(r-\frac{h}{3}\right)$$
$$Q = 2\pi \cdot r \cdot h$$

$$V = \frac{2}{3}\pi \cdot r^2 \cdot h$$

$$V = \pi \cdot r^2 \cdot h$$
$$Q = 2\pi \cdot r \cdot h$$

$$V = \pi \cdot r^2 \cdot \frac{h}{3}$$
$$Q = \pi \cdot r \cdot s$$
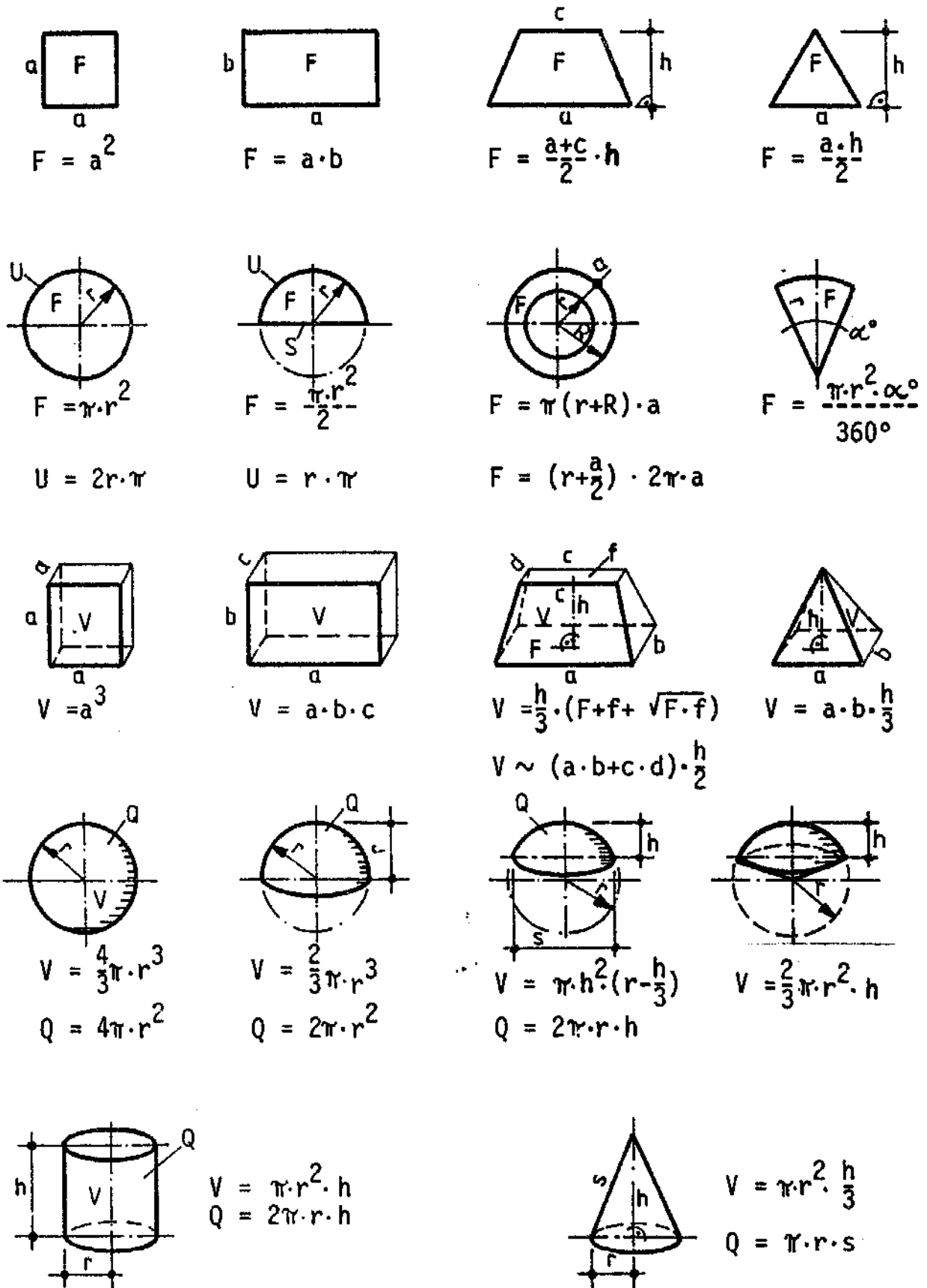
Fig. 10.11: Fundamental geometric formulae (Source: Sasse 1984)

10.4 Charts and Tables for Use in Performing Micro-economic Analyses

Notes on using the data sheet (table 10.10)

The data survey (data sheet, table 10.10) contains fictive, but nonetheless substantially realistic, data on a family-size biogas plant. Those data are referred to for explaining and calculating the arithmetic models described in chapter 8. Such data must be ascertained separately for each project site.

Notes on the individual data-sheet items

1. In order to keep the calculations uncomplicated, an unrealistically constant annual rate of inflation is assumed. It is possible to account for different inflation rates in the various analytical procedures. For explanatory details beyond those offered in this guide, please refer to Finck/ Oelert, chapter C III.
2. Calculatory interest rate, i: assumed rate of interest for evaluating the cash flows (income and expenditures) generated by a biogas plant during its technical service life. Proceeding on the assumption that expenditures are all the more burdensome, the earlier they fall due, while income is all the more valuable, the earlier it is earned, all cash flows occurring in connection with the investment are compounded/discounted at an assumed rate for a fixed point in time. Please refer to chapter 8.4 for the calculation procedure.
3. Investment costs (incl. wages):
   -- planning
   -- land acquisition/leasing (as applicable)
   -- civil works
   -- building and structures/digester

-- modification of animal housing
-- gas appliances/aggregates
-- slurry spreading implements
-- assembly and commissioning
-- customs, taxes, duties, fees
-- transportation
4. Manpower costs for:
-- feeding the plant
-- spreading the digested slurry
5. Maintenance and repair:
-- spare parts/materials
-- wages for maintenance/repair work
6. Energy revenues:
-- market value of replaced energy
-- energy supplied
-- production induced with extra energy (market value)
7. Revenues from fertilizer:
-- market value of replaced inorganic fertilizer
-- revenues from sales of digested slurry
-- higher cash-crop yields due to fertilizing with digested slurry
8. Time saved (real financial income only) for additional:
-- wage work
-- work on the farm (induced additional income)
9. Depreciation (annual for linear depreciation):

$$= \frac{\text{investment costs}}{\text{n (technical service life)}}$$

In this example, the technical service life of the plant is conservatively estimated at only 10 years.
10. Depreciation and capital-servicing costs (interest on loans): *neither* of these two factors is included as a cost factor in the dynamic models presented in chapter 8, because the cost of investment is equal to the sum of the cash values from depreciation and interest (cf. Brandt, 1982, for details). In this example, it is assumed that no external capital is needed, i.e. that the biogas plant is fully financed with internal capital.

Table 10.10: Data sheet for economic analysis (Source OEKOTOP; Finck/Oelert, Table 1)

Project title: .... Location: .... Owner: .... Type of plant/digester volume: ....
Technical service life: .... years

Item			Period 0	1	2	3	4	5	6	7	8	9	10
			Year 19 ..	19 ..	19 ..	19 ..	19 ..	19 ..	19 ..	19 ..	19 ..	19 ..	19 ..
1.1 General inflation rate 1)	%		34	34	34	34	34	34	34	34	34	34	34
1.2 Market interest rate, p	%		48	48	48	48	48	48	48	48	48	48	48
1.3 Assumed interest rate, i 2)	%		10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
2. Investment costs, I 3)	CU	1	100										
3.1 Manpower costs 4)	CU	–		–	–	–	–	–	–	–	–	–	–
3.2 Maintenance and repair 5) spare-parts requirement	CU	–		30	30	30	30	30	30	30	30	30	30
4.1 Taxes and levies not linked to profit	CU	–		–	–	–	–	–	–	–	–	–	–
4.2 Other expenditures	CU			50	50	50	50	50	50	50	50	50	50
5. Total operating costs, C_0				35	35	35	35	35	35	35	35	35	35
6.1 Energy-related revenues 6)	CU	–		210	210	210	210	210	210	210	210	210	210
6.2 Revenues from fertilizer 7)	CU	–		250	250	250	250	250	250	250	250	250	250
6.3 Time saved 8)	CU	–		–	–	–	–	–	–	–	–	–	–
6.4 Other income	CU	–		–	–	–	–	–	–	–	–	–	–
6.5 Subsidies	CU	–		–	–	–	–	–	–	–	–	–	–
7. Total income	CU	–		235	235	235	235	235	235	235	235	235	235
8. Returns (item 7 – item 5)	CU			200	200	200	200	200	200	200	200	200	200
9. Depreciation 9)	CU			110	110	110	110	110	110	110	110	110	110
10. Capital servicing costs 10)	CU	–		–	–	–	–	–	–	–	–	–	–
11. Profit	CU	–		90	90	90	90	90	90	90	90	90	90

CU = currency unit; in local currency or DM/US $ (conversion to DM/US $ rarely advisable due to fluctuating exchange rates)

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Table 10.11: Discounting factors for interest rates of i = 1–30% and periods of t = 1–30 years

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	.990	.980	.971	.962	.952	.943	.935	.926	.917	.909	.901	.893	.885	.877	.870
2	.980	.961	.943	.925	.907	.890	.873	.857	.842	.826	.812	.797	.783	.769	.756
3	.971	.942	.915	.889	.864	.840	.816	.794	.772	.751	.731	.712	.693	.675	.658
4	.961	.924	.888	.855	.823	.792	.763	.735	.708	.683	.659	.636	.613	.592	.572
5	.951	.906	.863	.822	.784	.747	.713	.681	.650	.621	.593	.567	.543	.519	.497
6	.942	.888	.837	.790	.746	.705	.666	.630	.596	.564	.535	.507	.480	.456	.432
7	.933	.871	.813	.760	.711	.665	.623	.583	.547	.513	.482	.452	.425	.400	.376
8	.923	.853	.789	.731	.677	.627	.582	.540	.502	.467	.434	.404	.376	.351	.327
9	.914	.837	.766	.703	.645	.592	.544	.500	.460	.424	.391	.361	.333	.308	.284
10	.905	.820	.744	.676	.614	.558	.508	.463	.422	.386	.352	.322	.295	.270	.247
11	.896	.804	.722	.650	.585	.527	.475	.429	.388	.350	.317	.287	.261	.237	.215
12	.887	.788	.701	.625	.557	.497	.444	.397	.356	.319	.286	.257	.231	.208	.187
13	.879	.773	.681	.601	.530	.469	.415	.368	.326	.290	.258	.229	.204	.182	.163
14	.870	.758	.661	.577	.505	.442	.388	.340	.299	.263	.232	.205	.181	.160	.141
15	.861	.743	.642	.555	.481	.417	.362	.315	.275	.239	.209	.183	.160	.140	.123
16	.853	.728	.623	.534	.458	.394	.339	.292	.252	.218	.188	.163	.141	.123	.107
17	.844	.714	.605	.513	.436	.371	.317	.270	.231	.198	.170	.146	.125	.108	.093
18	.836	.700	.587	.494	.415	.350	.296	.250	.212	.180	.153	.130	.111	.095	.081
19	.828	.686	.570	.475	.396	.331	.277	.232	.194	.164	.138	.116	.098	.083	.070
20	.820	.673	.554	.456	.377	.312	.258	.215	.178	.149	.124	.104	.087	.073	.061
21	.811	.660	.538	.439	.359	.294	.242	.199	.164	.135	.112	.093	.077	.064	.053
22	.803	.647	.522	.422	.342	.278	.226	.184	.150	.123	.101	.083	.068	.056	.046
23	.795	.634	.507	.406	.326	.262	.211	.170	.138	.112	.091	.074	.060	.049	.040
24	.788	.622	.492	.390	.310	.247	.197	.158	.126	.102	.082	.065	.053	.043	.035
25	.780	.610	.478	.375	.295	.233	.184	.146	.116	.092	.074	.059	.047	.038	.030
26	.772	.598	.464	.361	.281	.220	.172	.135	.106	.084	.066	.053	.042	.033	.026
27	.764	.586	.450	.347	.268	.207	.161	.125	.098	.076	.060	.047	.037	.029	.023
28	.757	.574	.437	.333	.255	.196	.150	.116	.090	.069	.054	.042	.033	.026	.020
29	.749	.563	.424	.321	.243	.185	.141	.107	.082	.063	.048	.037	.029	.022	.017
30	.742	.552	.412	.308	.231	.174	.131	.099	.075	.057	.044	.033	.026	.020	.015

Table 10.11 continued

t	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	.862	.855	.847	.840	.833	.826	.820	.813	.806	.800	.794	.787	.781	.775	.769
2	.743	.731	.718	.706	.694	.683	.672	.661	.650	.640	.630	.620	.610	.601	.592
3	.641	.624	.609	.593	.579	.564	.551	.537	.524	.512	.500	.488	.477	.466	.455
4	.552	.534	.516	.499	.482	.467	.451	.437	.423	.410	.397	.384	.373	.361	.350
5	.476	.456	.437	.419	.402	.386	.370	.355	.341	.328	.315	.303	.291	.280	.269
6	.410	.390	.370	.352	.335	.319	.303	.289	.275	.262	.250	.238	.227	.217	.207
7	.354	.333	.314	.296	.279	.263	.249	.235	.222	.210	.198	.188	.178	.168	.159
8	.305	.285	.266	.249	.233	.218	.204	.191	.179	.168	.157	.148	.139	.130	.123
9	.263	.243	.225	.209	.194	.180	.167	.155	.144	.134	.125	.116	.108	.101	.094
10	.227	.208	.191	.176	.162	.149	.137	.126	.116	.107	.099	.092	.085	.078	.073
11	.195	.178	.162	.148	.135	.123	.112	.103	.094	.086	.079	.072	.066	.061	.056
12	.168	.152	.137	.124	.112	.102	.092	.083	.076	.069	.062	.057	.052	.047	.043
13	.145	.130	.116	.104	.093	.084	.075	.068	.061	.055	.050	.045	.040	.037	.033
14	.125	.111	.099	.088	.078	.069	.062	.055	.049	.044	.039	.035	.032	.028	.025
15	.108	.095	.084	.074	.065	.057	.051	.045	.040	.035	.031	.028	.025	.022	.020
16	.093	.081	.071	.062	.054	.047	.042	.036	.032	.028	.025	.022	.019	.017	.015
17	.080	.069	.060	.052	.045	.039	.034	.030	.026	.023	.020	.017	.015	.013	.012
18	.069	.059	.051	.044	.038	.032	.028	.024	.021	.018	.016	.014	.012	.010	.009
19	.060	.051	.043	.037	.031	.027	.023	.020	.017	.014	.012	.011	.009	.008	.007
20	.051	.043	.037	.031	.026	.022	.019	.016	.014	.012	.010	.008	.007	.006	.005
21	.044	.037	.031	.026	.022	.018	.015	.013	.011	.009	.008	.007	.006	.005	.004
22	.038	.032	.026	.022	.018	.015	.013	.011	.009	.007	.006	.005	.004	.004	.003
23	.033	.027	.022	.018	.015	.012	.010	.009	.007	.006	.005	.004	.003	.003	.002
24	.028	.023	.019	.015	.013	.010	.008	.007	.006	.005	.004	.003	.003	.002	.002
25	.024	.020	.016	.013	.010	.009	.007	.006	.005	.004	.003	.003	.002	.002	.001
26	.021	.017	.014	.011	.009	.007	.006	.005	.004	.003	.002	.002	.002	.001	.001
27	.018	.014	.011	.009	.007	.006	.005	.004	.003	.002	.002	.002	.001	.001	.001
28	.016	.012	.010	.008	.006	.005	.004	.003	.002	.002	.002	.001	.001	.001	.001
29	.014	.011	.008	.006	.005	.004	.003	.002	.002	.002	.001	.001	.001	.001	.000
30	.012	.009	.007	.005	.004	.003	.003	.002	.002	.001	.001	.001	.001	.000	.000

10.5 List of Pertinent Suppliers and Institutions

Plant engineering, construction and consultancy services in developing countries

AIT Asian Institute of Technology -- Division for Energy Technology, P.O. Box 2754, Bangkok 10501, Tailand

AVARD Association of Voluntary Agencies for Rural Development, c/o Safdarjung Development Area, New Dehli, India

BORDA Bremen Overseas Research and Development Association, Bahnhofsplatz 13, 2800 Bremen, Federal Republic of Germany

Biogas projects: BORDA/UNDARP Poona, India

CEMAT Centro Mesamericano de Estudios sobre Tecnologia Apropiada, A.P. 1160, Guatemala-City, Guatemala

GATE/GTZ German Appropriate Technology Exchange/Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ) GmbH, Postfach 5180, 6236 Eschborn, Federal Republic of Germany

GATE/GTZ Biogas Extension Program Projects:

Projecto de Biogas c/o ENPRA, km 11.5 vieja a Leon, A.P. 4772 Managua, Nicaragua

Biogas Extension Service c/o CAMARTEC, P.O. Box 764, Arusha, Tanzania

Projet Biogaz Cankuzo, D/S 148, Bujumbura, Burundi

CDB/GATE Biogas Team c/o CDB, P.O. Box 407, Wildey St. Michael, Barbados

Proyeto Biogas PAAC-UMMS-GATE, Casilla 4740, Cochabamba Bolivia

Special Energy Program biogas projects (GTZ-Div. 34)

GTZ Special Energy Program, P.O. Box 41607, Nairobi, Kenya

Projet Special de l'Energie, c/o I.V.E., B.P. 5321 Ouagadougou, Burkina Faso

KVIC Khadi and Village Industries Commission, Gobar Gas Scheme, Ivla Rees, Vila Parle, Bombay 400 056, India

Maya Farms Angona, Rizal, Philippines

OEKOTOP Gesellschaft für Angepaßte Technologien in Entwicklungsgebieten, Bingerstr. 25a, 1000 Berlin 33, Federal Republic of Germany

Biogas projects (by order of GTZ):

Projet Biogaz c/o SODEPRA Ferkéssédougou, Côte d'Ivoire

Proyecto Biogas Columbo-Aleman c/o CVC, Apto. A2366, Cali, Colombia

RED-Latino Americana de Biogas, Emprater, W3 Norte Q515, Brazilia, Brazil

Equipment producers / suppliers

Elster AG, Postfach 129, 6500 Mainz, Federal Republic of Germany
Products: gasmeters

Kromschröder AG, Postfach 2809, 4500 Osnabrück, Federal Republic of Germany
Products: full range of gas valves

Metallurgica Jackwal Ltd., Rua Braz Cardoso 674, Vila Nova Canceicao, Sao Paulo, Brazil
Products: lamps, burners, reducing valves

OEKOTOP GmbH, Berlin
Product: portable biogas measuring set

Patel Gas Crafters Ltd., Shree Sai Bazar, Mahatma Gandhi Road, Bombay 400 054, India
Products: lamps, burners

Saron Vdyog, Shanghai, PR China
Products: gasmeters, lamps, burners

Service Centre for Development on New Energy, NO. 33 Fugiun Street, Shijiazkuang, PR China
Products: burners, motors

Shanghai Bioenergy, Shanghai, PR China
Products: gasmeters, lamps, burners, motors

T.A. Schiller, Postfach 1224, 2072 Bargteheide, Federal Republic of Germany
Products: lamps, burners, motors

Producers of biogas-fueled engines

Ford AG, Edsel-Ford-Str., 5000 Cologne 71, Federal Republic of Germany
– Type 2274 E, 15-25 kW, 1500–3000 min^{-1}, 4-cylinder, water-cooled, spark ignition

Henkelhausen, Postfach 9149, 4150 Krefeld 12, Federal Republic of Germany
– Series GFL 912, 19–40 kW, 1500–2300 min^{-1}, 3-, 4-, 5-, 6-cylinder, air-cooled, spark ignition
– Series GFL 413, 55–140 kW, 1500–2300 min^{-1}, 5-, 6-, 8-, 10-, 12-cylinder, air-cooled, spark ignition

Kirloska, India, German representative: Schule Co., Postfach 260620, 2000 Hamburg 26, Federal Republic of Germany
– Series AVG, TVG, CAG, TAG, 5–12 kW, 1200–2000 min^{-1}, 1-, 2-cylinder, air-cooled or water-cooled, dual-fuel

MWM AG, Carl-Benz-Str., 6800 Mannheim, Federal Republic of Germany
– Series G 227, 18–40 kW, 1500–2200 min^{-1}, 3-, 4-, 6-cylinder, water-cooled, spark ignition

10.6 Selected Literature

Biotechnical fundamentals and plant engineering

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Mémento de l'agronome, République Francaise, Ministére de la Cooperation, 1984
Rehm/Espig, Die Kulturpflanzen der Tropen und Subtropen, Stuttgart 1976
Williamson, G./Payne, W.J.A., An Introduction to Animal Husbandry in the Tropics, London/New York 1977

Economic aspects and dissemination/diffusion

Brandt, H., Projektplanung in der kleinbäuerlichen Produktion, Berlin 1982
Finck, H./Oelert, G., A Guide to the Financial Evaluation of Investment Projects in Energy Supply, GTZ Eschborn 1982
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10.7 Lists and Indexes

10.7.1 Illustrations

10.7.2 Tables

10.7.3 Photos

10.7.4 Abbreviations

A	area	COD	chemical oxygen demand
a	inflation rate	cp	coefficient of pipe friction
a	year (per annum)	cP	heat capacity
at	atmosphere	CS	crankshaft
		Cs	storage capacity
B	biomass		
B.D.C.	bottom dead center	D	density of biogas
BEP	GATE/GTZ Biogas Extension	D	energy demand
	Program	D, d	pipe diameters
BOD	biochemical oxygen demand	d	day
		d	stoichiometric air ratio
C	carbon	DN	density of biogas under normal
C	circumference		(s.t.p.) conditions
CaO	calcium oxide	dp	pressure drop
cd	candela (candle power)	Dr	digestion rate
ce	coefficient of earth pressure		
cf	coefficient of friction	E	illuminance
CH₄	methane	E·	compression ratio
cmWG	cm water gage	E	energy
C/N	carbon/nitrogen ratio	Ee	energy input
CO₂	carbon dioxide	Es	specific illuminance

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F	luminous flux	P	pressure/gas pressure
F	relative dampness of biogas	P	phosphorus
Fc (OH)$_3$	ferric hydrate	p	market rate of interest
FL	friction losses	p	biogas/energy production
		pa	Pascal
G	gas production	PE	polyethylene
gc, max	max. gas consumption per hour	pE	active earth pressure
GM	moisture content of gas	PN	normal pressure
Gp	specific gas production	P$_2$O$_5$	phosphorus pentoxide
GRP	glass-reinforced plastic	PVC	polyvinyl chloride
Gy	gas yield	PW	partial pressure of water vapor
		pw	hydrostatic pressure
H, h	height		
H$_2$	hydrogen	Q	gas flow
he	height of earth column	QW	quantity of heated water
hp	horsepower		
hph	horsepower-hour	R, r	radius
H$_2$S	hydrogen sulfide	Re	luminous efficiency
		ROI	retu.n on investment (profitability)
I	luminous intensity		
i	discounting factors/calculatory (assumed) interest rate	RT	retention time
lo	initial investment	Sd	daily substrate input
J	joule	T, t	temperature
		tc, max	maximum consumption time
K	potassium	T.D.C.	top dead center
K$_A$	average capital invested (per time interval)	tz, max	maximum period of zero consumption
kcal	kilocalorie	TN	temperature under normal (s.t.p.) conditions
K$_2$O	potassium oxide		
kWh	kilowatt hour	TS	total solids content
L	latent heat of evaporation	V	volume
l	length of pipe	v	velocity/speed
Ld	digester loading	vc	maximum gas consumption
lm	lumen	Vd	digester volume
		Vg	gasholder volume
mbar	millibar	Vh	compression volume
MgO	magnesium oxide (magnesia)	VN	volume of biogas under normal (s.t.p.) conditions
mWG	meter water gage		
		Vn	swept volume
N	nitrogen	VS	volatile solids content
N	burner efficiency	Vtot	total volume of a cylinder
N	Newton		
n.c.v.	net calorific value (in diagrams: n.c.v. = Hu)	W	water
NP	net profit	W	watt

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Wd	daily water input	wW	weight of water
wE	weight of dry earth		
W_1	water loss (leak testing)	Ztot	sum total of friction losses