Part I
General thoughts about energy supply

Human beings are the only animals with the ability to ignite and use a fire. This advantage has been important for the growth of mankind, particularly during the past few decades, when the rapid rate of innovation in industry was especially facilitated by the immense richness of oil. Today, thousands of oil platforms exist globally, which provide the oil for ca. 50 000 kWh of energy per year. Yearly, around 10 bn US$ are spent in drilling for new oilfields to secure the supply of oil and hence the base for industrial growth in future.

But, as with all fossil resources, the quantity of oil is limited and will not last for ever. A time will come for sure when all the existing accessible oil fields will have been exploited. What will then happen to mankind?

May the same happen as is observed in nature? Not only in animals but also in plants there are sudden “explosions of populations”. Such growth naturally stops, however, as soon as a source of life runs dry. The organisms start suffering from deficiency symptoms and become dominated or eaten by stronger organisms.

How will human beings generate energy when all the oil resources we benefit from today are fully consumed? There is as yet no clear answer to this question. But regardless of what the answer may be, it is clear that the mankind will always want to continue building huge inventories of energy. With the declining quantity of fossil fuels it is critical today to focus on sustained economic use of existing limited resources and on identifying new technologies and renewable resources, e.g., biomass, for future energy supply.

Biogas from Waste and Renewable Resources. An Introduction.
Dieter Deublein and Angelika Steinhauser

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1
Energy supply – today and in the future[1)]

Today, globally most energy is provided by burning oil. Only a very small percentage is generated by nuclear power plants. The contribution of energy from renewable resources is almost negligible. But this will change in the future with increasing prices of oil.

In the future, countries may use different technologies, depending on their climatic and geographical location. Germany refrains from using nuclear power plants as a source of energy. This makes Germany one of the leading countries in the development of technologies for alternative and renewable energy sources.

1.1
Primary energy sources

In general, primary energy sources are classified as follows:

Fossil energy sources
- Hard coal
- Brown coal
- Petroleum
- Natural gas
- Oil shale
- Tar sand
- Gas hydrate

Renewable energy sources
- Water
- Sun
- Wind
- Geothermal heat
- Tides
- Biomass

Nuclear fuels

1) Cp. BOK 1

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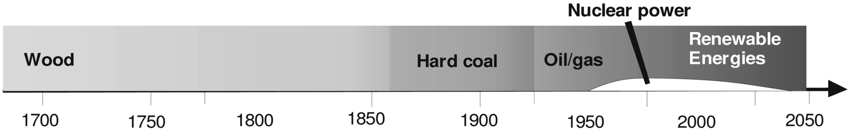

Figure 1.1 Life cycles of primary energy sources.

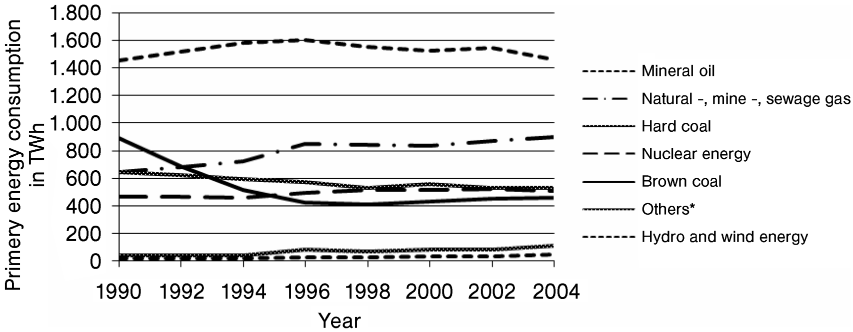

Figure 1.2 Primary energy sources related to the total consumption of primary energy resources in Germany in TWh[2] during 1990–2004 (*e.g., firewood, turf, sewage sludge, waste, and other gases).

These primary energy sources follow so called "life cycles" as shown in Figure 1.1.

Until the late 19th century, wood, the traditional biomass, was the only primary energy source used for cooking and heating. This ended when wood was replaced by hard coal, an epoch which lasted ca. 75 years. This was followed in the late 1950s by a continuously increasing use of petroleum and natural gas. Around 1950, nuclear power technology was first time industrialised, but it never became truly accepted. For some years now, this technology has remained stagnant and has not expanded because of still unresolved issues such as the storage of the radioactive waste and the risk of explosion of a reactor. This leaves "renewable energies", showing the biggest potential for securing the availability of energy in the future.

As an example: the total consumption of primary energy in Germany is ca. 4100 $TWh\,a^{-1}$, which has been provided by the use of different primary energy sources, shown in Figure 1.1. The primary energy source used during the past few years in Germany was mainly mineral oil (Figure 1.2). In the early 1990s, quite a significant part of energy in the Eastern part of Germany was also generated by processing brown coal. After the German reunification, however, the mining of brown coal was stopped because of the great environmental damage it was causing.

2) Cp. WEB 20

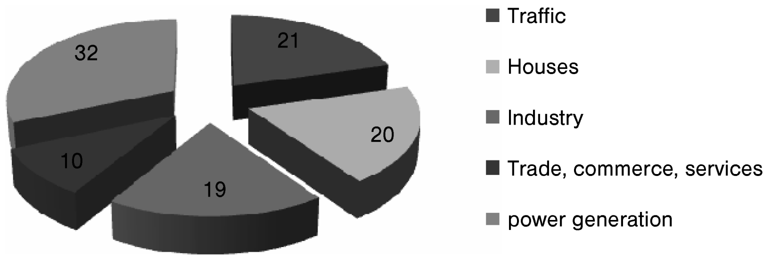

Figure 1.3 Primary energy as resource in % – segmentation in industrialized countries.

After this, the consumption of energy provided by hard coal remained almost static, while the energy from natural gas, mine gas, or sewage gas strongly increased to make up for that previously provided by brown coal. The use of renewable energy has been almost static during recent years, with a very slight though consistent upward trend.

Consumers using primary energy are shown in Figure 1.3. This chart shows that the traffic sector consumes 21% of the primary energy, which is even more than industry (19%). In fact the amount of energy supplied to industry is decreasing, and increasing amounts go to traffic. This is explained by the current trend toward a society with a high number of cars per family leading to a high demand of petrol, a secondary energy source of petroleum.

1.2 Secondary energy sources

Secondary energy sources are defined as products that have been produced by transforming primary energy carriers into higher quality products by applying processes such as refining, fermentation, mechanical treatment, or burning in power stations:

Products derived from coal
- Coke
- Briquettes

Products derived from petroleum
- Petrol
- Fuel oil
- Town gas
- Refinery gas

Products derived from renewable resources
- Biogas
- Landfill gas
- Pyrolysis gas

The secondary energy sources are converted to end-point energy.

1.3
End-point energy sources

The end-point energy is the energy used by the final consumers and provided in form of, e.g. district heating, wood pellets and electricity. In Germany, for example, the consumption of end-point energy is about 2600 TWh a^{-1}. It is important to emphasize that only electricity and not gas is defined as end-point energy since gas is the energy source that electricity is derived from.

Usually the amount of end-point energy consumed is used for calculation purposes and is taken as a base to reflect energy balances.

1.4
Effective energy

Only about 1/3 of the primary energy is effective energy which is actually used by customers in form of heating, light, processing, motion, and communication. The other 2/3 is lost when transforming the primary energy sources into effective energy. As an example, in Germany only 1400 TWh a^{-1} of energy is effectively used. About 570 TW a^{-1} of this energy is actually electricity. To cover these quantities, the electricity is produced mainly by using fossil energy sources (60%) like hard coal, petroleum, or natural gas (Figure 1.4); 30% is derived from nuclear power stations, while the amount of electricity from renewable energy sources is only about 7.25% to date.[3)]

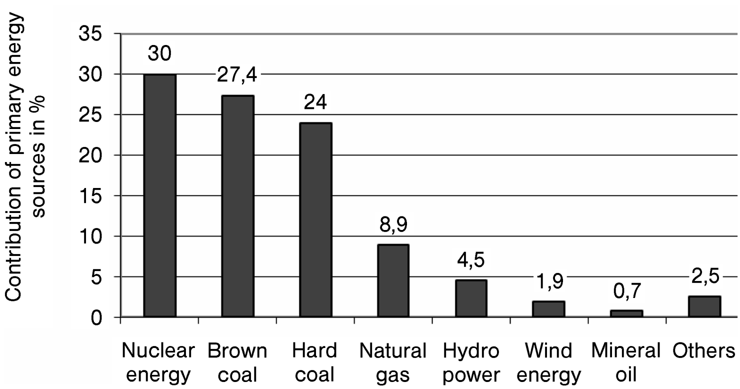

Figure 1.4 Electricity supply in Germany – Contribution of primary energy carrie's on total power supply.

3) Ср. BOK 3

2
Energy supply in the future – scenarios

Shell International[4] has published a projection for different energy sources for the years 1990 up to 2100 (Figure 2.1). Assuming the "Sustainable Growth" scenario, energy consumption will increase by 7 times (at most) during this period. Applying the "Dematerialization" scenario (= much lower consumption driven by sustained economic use), the amount of energy will increase by a factor of 3 (at least). Both scenarios can be explained and are driven by the assumptions of an increase in population from about 6 bn to around 10 bn plus a continuous fast path taken by emerging markets to accelerate their economic growth.

Further, by 2020 the technologies around renewable resources are expected to have reached the potential for full economic use. Shell foresees a fast growth for these future alternatives and has projected that by 2050 the regenerative energy resources will provide 50% of the total energy consumption worldwide. According to Shell, the main source will be solar energy and heat.

Similarly, the WEC (World Energy Council) in 1995 has put forward a scenario in which the primary energy consumption will increase 4.2-fold by 2100 (referring back to 1990), and in its "Ecological" scenario of 1995 it still talks about a 2.4-fold increase.[5]

The IPCC (International Panel on Climate Change) expects a 3 times higher energy consumption by 2100 (referring back to 1990), providing a high demand. With sustained economic use of energy, calculations suggest that almost 30% of the total global primary energy consumption in 2050 will be covered by regenerative energy sources. In 2075 the percentage will be up to 50%, and it is expected to continuously increase up to 2100. According to the IPCC report, biomass is going to play the most important role, projected to deliver 50 000 TWh in 2050, 75 000 TWh in 2075, and 89 000 TWh in 2100, in line with the calorific value derived from the combustion of more than 16 bn Mg of wood.[6]

Many other institutions have developed their own scenarios and done their own projections, as shown in Table 2.1.

The economic potential of using hydroelectric power to provide energy is already almost fully exploited. All other renewable resources, however, still have huge potential and can still be widely expanded.

4) Cp. WEB 65
5) Cp. WEB 79
6) Cp. WEB 72

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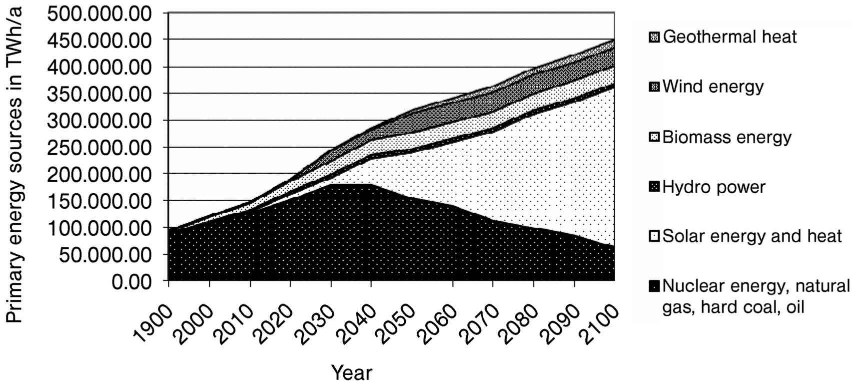

Figure 2.1 Projection of the energy supply up to year 2100 (acc. to Shell International).

Table 2.1 Perspectives for energy sources as a percentage of the total energy consumption in Germany.

	Federal Ministry for the Environment in Germany[7]				*Federal Ministry of Economy and Technology in Germany*[8]		*Greenpeace*[9),10)]	
	Today		*Projection in year 2080*		*In 2020*		*In 2010*	
Total final energy consumption	*Static at around 2600 TWh a⁻¹*				*Static*	*Declining to ca. 2115 TWh a⁻¹*	*Independent of the energy consumption*	
	Elect.	*Heat*	*Elect.*	*Heat*			*Elect.*	*Heat*
Natural gas	21.9		0		28.0	41.0	4.1	30.2
Nuclear energy	12.9		0		4.0	2.0		
Hard coal	13.2		0		22.0	11.0	2.4	5.6
Brown coal	11.6		8					
Petroleum	37.5		0		41.0	36.0		18.8
Renewable energy	1.31	1.59	24.0	68.0	4.0	10.0	18.5	20.4
Hydro-electricity	0.60		1.5				4.1	
Wind	0.40		8.5				4.8	
Photovoltaics	0.01		4.3				2.8	
Solarthermal heat		0.07		25.0			2.6	0.2
Geothermal heat		0.04	10.0	35.0			3.0	0.2
Biomass	0.30	1.48	3.0	8.0			1.2	20.0

Note: Technical final energy potential = technically usable electrical energy in the system.

7) Cp. WEB 23
8) Cp. WEB 26
9) Cp. WEB 66
10) Cp. JOU 13

Biomass is rich in carbon but is not yet a fossil material. All plants and animals in the ecological system belong to biomass. Furthermore, nutrients, excrement, and bio waste from households and industry is biomass. Turf is a material intermediate between biomass and fossil fuel.

There are several processes to transform biomass into solid, liquid, or gaseous secondary energy carriers (Figure 2.2): these include combustion, thermo-chemical transformation via carbonization, liquefaction or gasification, physico-chemical transformation by compression, extraction, transesterification, and biochemical transformation by fermentation with alcohol or aerobic and anaerobic decomposition.

Today in Germany, 65% of the heat and electricity generated with processes based on biomass are provided by combusting firewood and forest residual wood, followed by the use of industrial residual wood and matured forest. About 14% of the energy comes from the use of liquid or gaseous biological energy carriers. When considering heat only, it is even higher, as shown in Table 2.2.

Thermochemical processing or combustion are the most effective ways to maximize the generation of energy. Combustion is only efficient, however, if the water

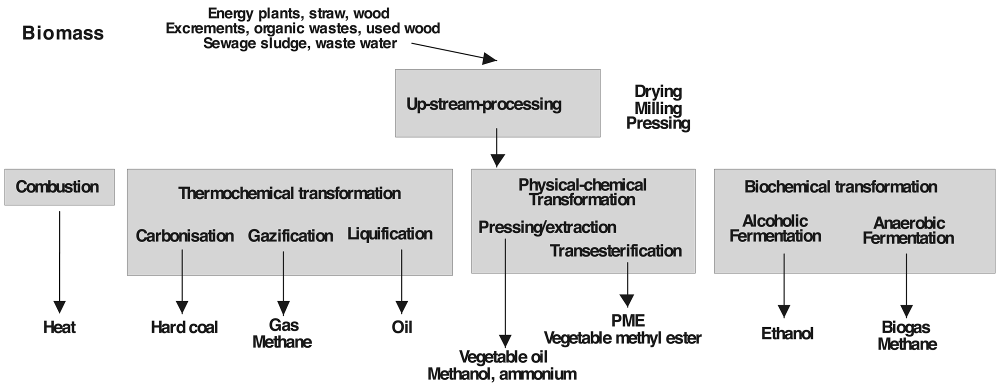

Figure 2.2 Applied technologies to transform biomass[11] into secondary energy sources.

Table 2.2 Heat generated from biomass.

Energy carrier	*Percentage*	*Generated heat*
Organic residues. By-products, waste (biogas, sewage sludge gas, landfill gas)	9.4	6.25–6.53 TWh a^{-1}
Bio fuels	1.3	0.8–0.9 TWh a^{-1}
Biogenous solid fuel (firewood, forest residual wood)	89.3	45.8 TWh a^{-1}
Industrial residual wood		11.9 TWh a^{-1}
Matured forest without recovered paper		3.3 TWh a^{-1}
Other wood-like biomass		0.3 TWh a^{-1}
Straw		0.78 TWh a^{-1}

11) Cp. JOU 16

content of the biomass is below 60% to prevent most of combustive energy from going into the evaporation of water. In the worst case, all this energy will have to be generated from the flue gas. The only chance to regain this usable energy will then be to condense the evaporated water in a condensing boiler.[12] However, this is only possible if the biomass is free from corrosive materials. From an economic point of view, the temperature of the flue gas is important. Furthermore, the composition of the combustion residue needs to be carefully evaluated for possible use.

If the biomass has very high water contents (e.g., liquid manure, freshly harvested plants), it is best to select and accept a process which provides only about 70% of the energy resulting from the combustion of dry material. As an advantage, the residues can be easily returned to nature, especially since no materials enriched with minerals and thus plant-incompatible ash are generated.

If biomass is to be used to serve as source win liquid fuel, it is best to produce ethanol and/or methanol via alcoholic fermentation. This process is more efficient than anaerobic fermentation referring to the hectare yield.

Overall, the energy balance is particularly favorable for biomass when considering the energy yield from the biomass [output] to the assigned primary energy [input], including all efficiencies as to be seen in Table 2.3.

With the output/input ratio of 28.8 MJ/MJ, biomass appears to be a very efficient source of biogas.

One of the leading countries in developing biogas plants is Germany, where hence a lot of efficiency data have been yet generated. In the following abstracts, these data are presented to show the potential of this technology and to highlight important factors that should be considered before planning a biogas plant. It is

Table 2.3 Energy balance[13),14)] for different final energy carriers.

Energy source	*Energy balance Output/ Input [MJ/MJ]*	*Remarks*
Rape oil	5.7	Energy recovery of the colza cake and green waste included
Ethanol	2.7	From wheat
Ethanol	1.6	From sugar beet
Ethanol	5.0	From sorghum Energy recovery of the bagasse included
Electricity and heat	8.5	Combustion of the whole plant From cereals
Electricity and heat	19.7	Combustion of miscanthus plants (not dried)
Electricity and heat	14.2	Combustion of energy plants
Electricity and heat	20.4	Combustion of residual straw
Electricity and heat	19.0	Combustion of forest residual wood
Biogas	28.8	From excrement (CHP cycle)

12) Cp. BRO 3
13) Cp. BRO 16
14) Cp.: BOK 62

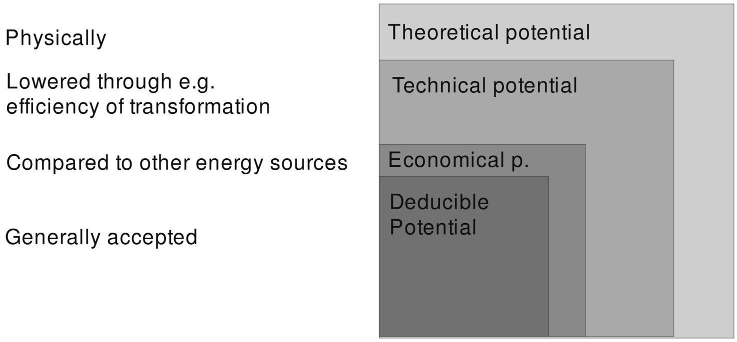

Figure 2.3 Evaluation of the scope – from the theoretical to the deducible potential.

important to differentiate and carefully evaluate the theoretical, technical, economical, and realizable potential (Figure 2.3).

The theoretical potential comprises all the energy that should theoretically be physically generated within a defined time period and a defined space.

The technical potential is part of the energy of the theoretical potential. It is that specific part which can be provided within the given structural and ecological boundaries and by respecting any legal restrictions.

It may not always make sense to fully exhaust the technical potential, especially if there is no profitable return.

However, the economic potential may not be realizable without any administrative support from certain institutions.

The total yield from biomass results from the maximum area available for cultivation and the energetic yield from the biomass cultivated on this specific area.

2.1 Amount of space

The amount of space in Table 2.4 is defined as the land area plus the surface area of the water, because algae or water plants in general are biomass and may have potential in the future.

The right hand columns in the table show the amount of space that is available for cultivation of biomass and may have potential.

In theory all the amount of space A_D, including the surface of the water, can be used to produce biomass.

Technically, biomass can be cultivated on all areas except the settlement area, mining lands or badlands. This is an amount of space of $A_{Dtechn} = 0{,}88 \cdot A_D$ of the total surface of Germany.

As soon as the micro algae production is developed, then technically an even larger surface, means 95% of the entire available space, could be exploited.

Economically, the cultivation of energy plants competes with the cultivation of other agricultural products. The market will probably equilibrate itself. But overall

Table 2.4 Total available area in Germany as A_D in hectares [ha].[15)]

Utilization of the amount of area today		*Total area*	*Theoretically usable*	*Technically usable*	*Economically usable*
Total		35 703 099	35 703 099	31 503 678	20 117 031
Settlements and areas used for transport and traffic		4 393 895	=	374 052	300 812
The above areas include:	Buildings and open space including residences, trade, industry	2 308 079	=	0	0
	Areas for winning substances out of the soil without mining land	73 240	=	=	0
	Area for recreation incl. parks	265 853	=	=	=
	Area for cemeteries	34 960	=	=	=
	Areas for traffic (roads, streets)	1 711 764	=	0	0
Area for agriculture including moor and heathland		19 102 791	=	=	9 551 395
Forest area		10 531 415	=	=	=
Surface of the water including sea		808 462	=	=	0
Mining land		179 578	=	0	0
Other areas		686 957	=	=	0
These include:	Badlands	266 593	=	=	0
			100%	88%	56%

= means same number as in the left column.

15) $1\,km^2 = 100\,ha = 10\,000\,a = 1\,000\,000\,m^2$

about 50% of the agricultural area is considered to be available for profitable production of biomass. Some other surfaces will never be agriculturally usable in a profitably way. So the total area for profitable agricultural use for biomass is estimated to be $A_{Dtechn} = 0.56 \cdot A_D$.

2.2 Potential yield from biomass

2.2.1 Theoretical potential[16)]

Biogas results from the microbial degradation of biomass, formed by photosynthesis by solar power E_S.

$$6CO_2 + 6H_2O + Es \rightarrow C_6H_{12}O_6 + 6O_2$$

$$\text{Carbon dioxide} + \text{Water} + \text{Solar energy} \rightarrow \text{Sugar (Glucose)} + \text{Oxygen}$$

Metabolic processes in the plants, transform the following compounds into secondary products.

Carbohydrates:	Starch, inulin, cellulose, sugar, pectin
Fat:	Fat, fatty acids, oil, phosphatides, waxes, carotene
Protein:	Protein, nucleoproteid, phosphoproteid
Others:	Vitamins, enzymes, resins, toxins, essential oils.

During the metabolism of the sugar, the plant releases energy, when necessary, to the environment, so that the possible energy yield from plants may vary greatly.

Multiplying the proportion of the main plant components (see Table 2.5) by the entire vegetation, an averaged elementary composition of plants dry matter results:

$$C_{38}H_{60}O_{26}$$

With the help of an approximate equation from Buswell (1930), the theoretical maximum yield of methane can be estimated taking the elementary composition as a base:

$$C_cH_hO_oN_nS_s + y\,H_2O \rightarrow x\,CH_4 + (c - x)CO_2 + n\,NH_3 + s\,H_2S$$

Table 2.5 Main components of plants without nitrogen N and sulfur S.

Carbohydrate	$C_6H_{12}O_6$
Fat	$C_{16}H_{32}O_2$
Protein	$C_6H_{10}O_2$

16) Cp. WEB 18

where

$$x = 0.125\,(4c + h - 2o - 3n + 2s)$$
$$y = 0.250\,(4c - h - 2o + 3n + 2s)$$

or, simplified

$$C_cH_hO_o \rightarrow (c/2 + h/8 - o/4)CH_4$$

The hectare yield of methane can hence be calculated from the hectare yield of the dry matter. This again depends on the planting, which should be as productive as possible.

The maximum theoretical possible yield is estimatedat $E_{Rmax} = 30\,MgDM/(ha \cdot a)$ when applying two harvests per year and cultivating C4 plants with an average elementary composition of $M_E = 932\,kg/kmol$. Based on the simplified equation from Buswell the yield of CH_4 is $E_M = 20\,kmol\,CH_4/kg$ biomass and the energy yield P_{theor} is calculated by the formula:

$$\overline{P}_{theor} = \frac{E_{R\max}}{M_E} \cdot E_M$$

to give $144.200\,kWh/(ha \cdot a)$. If one multiplies the hectare yield by the entire surface of Germany (35 703 099 hectares), the following equation

$$P_{theor} = \overline{P}_{theor} \cdot A_D$$

results in a primary energy quantity from biomass of $5.148\,TWh/a$. Theoretically the entire amount of primary energy supply in Germany could be covered by biomass alone.

Assuming that the yield of the available cultivable area on earth is proportionally the same as in Germany, an area of 7 420 Mio ha, half of the available area of 14 900 Mio ha on earth, would theoretically be enough to cover the total world primary energy consumption of $107\,000\,TWh\,a^{-1}$.

If a precondition is that the maximum yield should be guaranteed on a long-term basis, this could be facilitated by

Accurate and targeted addition of fertilizer
Water and fertilizer can be added very accurately by using hoses which are directly led to the roots. The accuracy depends on the characteristics of the local soil, but the overall yield per hectare of conventional agriculture could perhaps be doubled, particularly, when some missing nutrients are supplied with the water.

Multiple harvests per year
Yields of 25–30 Mg DM/ha.a can be obtained if the field crops shown in Table 2.6 are cultivated immediately after each other during one year.[17),18)]

17) Cp. JOU 26

18) Cp. JOU 32

Table 2.6 Crop rotation (GPS = Mixture of winter wheat and peas).

1st Planting	*2nd Planting*	*3rd Planting*
Wheat	Maize (mass-producing species)	GPS
Winter rye	Sunflower	
Winter barley	Sorghum	
Triticale,	Sudan grass	
Winter oat	Hemp	
Winter rape	Mustard	
Beets	Phacelia	
Winter peas	Radish	
Incarnat clover	Sweet pea	
Winter sweet pea	Peas	

Today the most frequently cultivated crop rotation consists of the following three crops:

1. The domestic cold-compatible C3 plants: winter rape or winter rye
2. The southern C4 plants: corn (mass-producing species),[19] as main crop during summer
3. The cold-resistant C3 plants: GPS.[20]

In order to generate energy, all the plants are harvested as soon as they finish their growth without leaving them time to fully develop. The costs of cultivation are 61–84 US$/Mg for the cultivation of winter wheat, winter barley, and triticale a crossing of wheat and rye in Germany.[21]

Overall the cultivation of energy plants has just started. Besides maize, some other C4 plants like sorghum, sugar cane, or Chinese reed seem to be efficient when used as biomass.[22] Their yield, though, still needs to be improved. Also, certain C3 plants such as grain, grasses, hemp, rape, beet, sunflower, or winter peas seem to have good potential as energy sources with a yield still to be increased, too. In future this broader range of energy plants will allow interesting new combinations and an increased level of flexibility in deciding on the crop rotation system.

2.2.1.1 **C3 plants (energy plants)**

The enzyme most important for the production of energy is RuBisCo (Rubilose 1.5-diphosphate carboxylation-oxygenase). It is the most frequently produced enzyme of all organisms and can be found in the chloroplasts of the plants in the form of proteins. Their level in the proteins amounts to 15%.

RuBisCo catalyzes photosynthesis and photorespiration. It binds oxygen as well as CO_2 and acts as oxygenase. For photorespiration to occur, the chloroplasts,

19) Cp. WEB 11
20) Cp. JOU 30
21) Cp. WEB 89
22) Cp. BOK 72

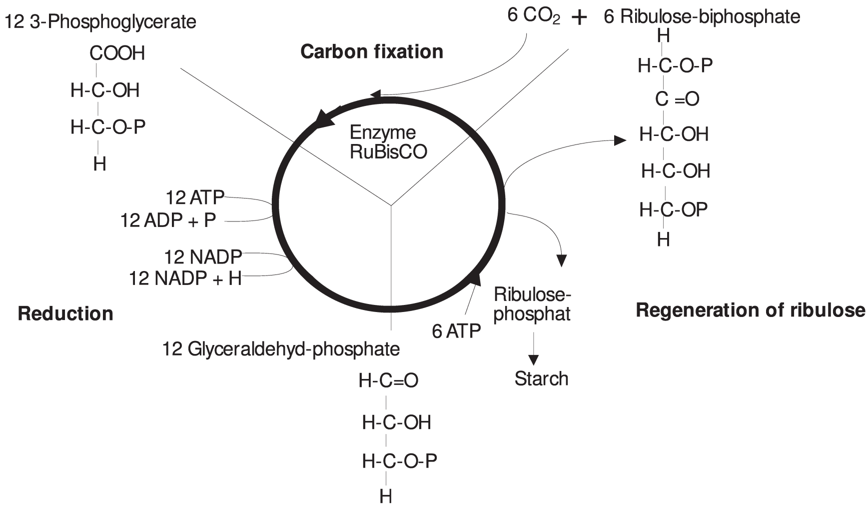

Figure 2.4 Calvin cycle.[23)]

mitochondria, and glyoxisomes, cell components around the mitochondria, need to be involved.

The ratio of photosynthesis to photorespiration is defined by the ratio of CO_2 and O_2 in the air. With a higher concentration of CO_2, the output of the photosynthesis increases.

In moderate zones, e.g., in Central Europe, photorespiration in plants plays a subordinate role. Predominantly C3 plants occur, which use the light-independent reaction, the Calvin cycle (Figure 2.4), to bind CO_2. They are called C3 plants, because the first stable product in the Calvin cycle after the CO_2 fixing 3PGS (Phosphoglycerate) has 3 C-atoms. Also the molecule which is reduced from 3PGS with NADPH+H+ to 3PGA (Phosphoglycerin aldehyde) in the following phase of the Calvin cycle contains 3 C-atoms.

The leaf structure of C3 plants is layer-like. In warm summer weather the transpiration and the evaporation at the surface of the sheets increases. In order to minimize the water loss, the plants close their pores. CO_2 cannot be absorbed by the pores any longer. Thus the photosynthesis is stopped and the biomass yield is limited.

In addition, the biomass yield depends on the soil as well as the entire climatic conditions: in some regions of the world the yield can be up to five times higher than in Germany. It is not possible, however, to obtain the theoretically projected yields just by cultivating C3 plants (Table 2.7).

Other typical representatives of C3 plants are onions, wheat, bean, tobacco.

Most C3 plants are well adapted to the moderate climatic zones but not to arid, saline areas with hot and dry air. Under such climatic conditions the ratio of photosynthesis to photorespiration increases from 2 : 1 and negatively impacts the yield.

23) Cp. WEB 31

Table 2.7 Yield per hectare of C3 plants.

Plant	*Yield [Mg DM (fruit + haulm)/ ha.a]*[24]	*Water content [%] related to the total mass*	*Advice for plantation*
Trees (stored)	1–2	15–20	Cut every 150 years
Fast-growing wood (poplar, willow)	15	30–60	Cut every 6 years
Eucalyptus	15–40	High	–
Rape (whole plant)	4.2–6.9	12–34	Crop rotation every 4 years
Sunflower (mature plant)	2.5	15	Crop rotation every 5 years
Hemp	3–4	65–75	Crop rotation yearly
Sugar beet	7.2–18.2	74–82	Crop rotation every 4 years
Potato	5.8–12.5	75–80	Crop rotation every 4–5 years
Jerusalem artichoke	12–27	72–81	Crop rotation yearly
Straw and grain	4–15	14–16	Crop rotation yearly
Bastyard Grass[25]	13.7	65–80	For 5 cuts per year
Meadow	7.7	65–80	For 5 cuts per year

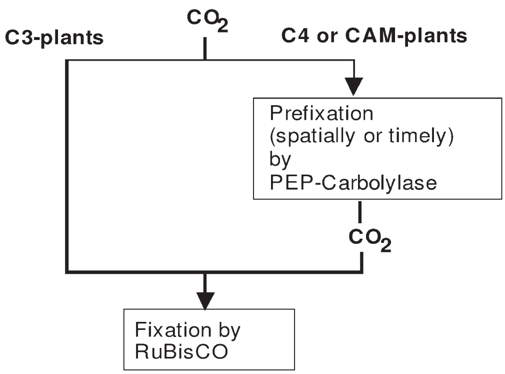

Figure 2.5 Different ways for the CO_2-Fixation.

2.2.1.2 C4 plants and CAM plants

There is a large group of 1700 variants of C4 plants and/or CAM plants which are all well adapted to hot and dry climates and do grow in arid, saline areas. This is possible since the CO_2 fixing occurs in C4 plants spatially separated from where the Calvin cycle occurs. In CAM plants the CO_2 fixing happens at a different time of the day from that when the Calvin cycle occurs (Figure 2.5). Such plants can utilize even the smallest CO_2 concentrations.

The separation of the CO_2 fixing occurs with the help of the enzyme PEP carboxylase (PEP = phosphoenolpyruvate), which possesses a substantially higher affinity

24) $1\,km^2 = 100\,ha = 10\,000\,a = 1\,000\,000\,m^2$

25) Cp. WEB 90

to CO_2 than RuBisCo. The first product of the photosynthesis which is stable is oxalacetate (see Figure 2.7), a C4 product. This characterizes the so-called C4 plant.

Compared to C3 plants, the leaves of C4 plants are anatomically different. The spatial separation of the CO_2 fixation takes place in cells at a distance from each other, the bundle sheath cells and the mesophyll cells, both containing chloroplasts but different types: the mesophyll cells contain normal chloroplasts while the budle sheath consist of chloroplasts with grana. The vascular bundles to transport the cell liquid are covered by a layer of thick bundle sheath cells which are surrounded by mesophyll cells.

An intensive mass transfer is continuously happening between the bundle sheath cells and the mesophyll cells. This starts with the formation of oxalacetate (Figure 2.6), a result of the enzymatic reaction of PEP-carboxylase binding CO_2 to PEP = (phosphoenolpyruvate). Oxalacetate is then enzymatically transformed into malate and transferred to the chloroplasts of the bundle sheath cells. In the bundle sheath cells it degrades into pyruvate and CO_2 while forming NADPH+H+ as a by-product. CO_2 is introduced into the Calvin cycle while pyruvate is transported back into the mesophyll cells.

CAM plants actually belong to the group of C4 plants. The name “CAM plants” is derived from the Crassulaceae Acid Metabolism (acid metabolism of the Crassulaceae), since the metabolism was first observed in the plant species “Crassulaceae”.

Because of the high water loss, these plants open their stomata only at night to take up CO_2 which is stored in form of malate. During the day, CO_2 is released and transformed in the Calvin cycle forming ATP as a by-product.

Like C3 plants, the CAM plants have layer-like structured leaves.

Some species of CAM plants are cactuses, pineapple, agave, Kalanchoe, Opuntia, Bryophyllum, and the domestic Sedum spec. or Kalanchoe (Crassulaceae).

C4 and/or CAM plants show the following advantages, compared to C3 plants:

- C4 and/or CAM plants can generate biomass twice as fast if conditions are favorable (see Table 2.8).
- The upper leaves of C4 and/or CAM plants are perpendicularly directed to the sun, so that the low-hanging leaves still get sufficient light even under unfavorable light conditions.

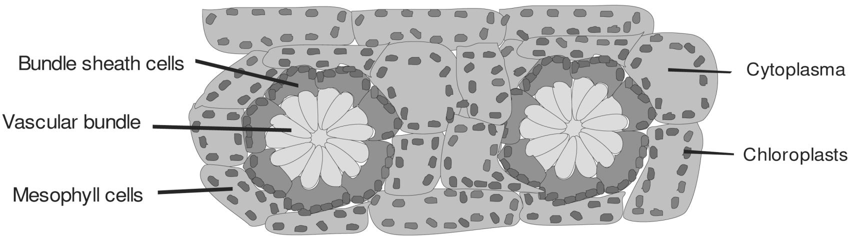

Figure 2.6 Anatomy of the leaves of a C4 plant.[26]

26) Cp. BOK 4

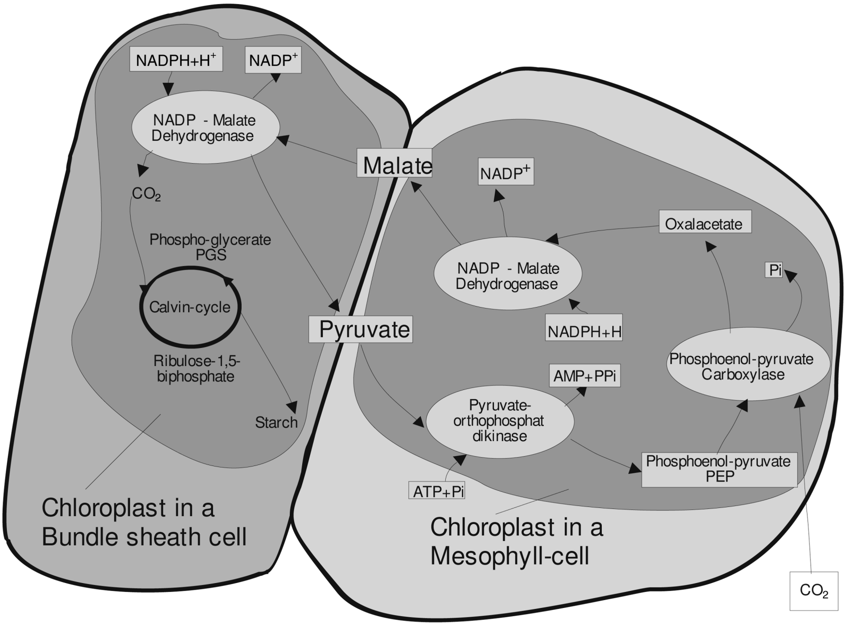

Figure 2.7 Mass transfer in C4 plants (C4-dicarbon acid path).[27]

Table 2.8 Yields of C4 plants (CAM plants are less productive).

Plants	*Max. yield (approximate)*	*Water content (depends on harvest time)*	*Advice for plantation*
	[Mg_{DM}/ha.a] (fruit+haulm)	*[%]*	*[Years]*
Miscanthus	25–30	15–45	Harvesting 20–25 from the 3rd year on
Sorghum spec.	17	17–60	Harvesting 20–25 from the 3rd year on
Sorghum spec.	5–32	70–80	One year plant
Maize	30[28]	15	One year plant

- C4 and/or CAM plants need only half the water.
- C4 and/or CAM plants adapt to dry and warm locations.
- C4 and/or CAM plants do not need pesticides but only some fertilizers in the first year.

27) Cp. BOK 4

28) Cp. JOU 18

Figure 2.8 Sorghum (above right), Micro-algae chlorella in glas tuber (below). Energy maize abt. 5 m heigh (above left).

- C4 and/or CAM plants once planted grow again after biomass has been harvested.

2.2.1.3 **Micro-algae**

By cultivating micro-algae, even the surface of water as well as the area of rooftops can be exploited in a profitable way.

A yield of 15–17 Mg biomass per year seems theoretically be achievable by planting micro-algae and cultivating them in well-lit bioreactors.[29)]

29) Cp. WEB 91

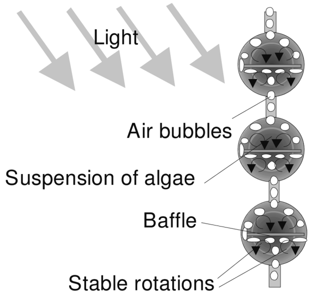

Figure 2.9 Reactor for micro-algae growth.

Most of the micro-algae naturally grow much better when the light is somewhat diffused rather than in direct clear light. Sun may even limit the growth. In order to control the light in the latest bioreactors, the micro-algae are cultivated in airlift reactors in which a circular flow is caused by changing the direction of the gas bubbles (Figure 2.9). The light reflects at the outer wall of the reactor.

The circular flow is set in such a way that the algae are located mainly in the outer area of the incidence of light. The algae absorb just enough light to keep the Calvin cycle alive for a maximum yield of biomass.

In reactors erected in the sea, the sea water can actually be used to help maintain a moderate temperature inside the reactor. The micro-algae may also serve to clean the water, especially in cases where the reactor is located close to a river mouth and the water is led through the reactor.

Micro-algae can not only be used to produce biogas but also to provide lipids, fatty acids, vitamins, e.g., vitamin E, beta-carotene, or even pigments like phycocyanin or carotenoids. Antioxidants like tocopherols or omega fatty acids may also be extracted, which are very interesting from a pharmaceutical point of view.

In 2000 the first farm for micro-algae was inaugurated close to Wolfsburg, in the middle of Germany. Within a fully closed system of bio-reactors (about 6000 m^3 in total) chlorella algae are converted into about 150–200 Mg animal food produced annually.[30]

2.3 Technical potential[31]

Technically it should soon be feasible to achieve a yield of $E_R = 1/2\ E_{Rmax} = 15\ Mg/ha.a$ of biomass.[32] This final effective outcome may be lower than the theoretical potential, since certain losses have to be taken into consideration because

30) Cp. WEB 92
31) Cp. BOK 5
32) Cp. WEB 69

- Quite often the biomass that is used to generate the energy is just a leftover after having been consumed as food. Some other parts of biomass had been used to construct houses. . . . Overall most of the quantity of biomass effectively used has served other purposes before being taken for energy supply, so that part of the energy has already been wasted.
- Technically the transformation from primary energy to effective energy goes along with quite immense losses of around 20–70%.
- Energy plants need to be cultivated in a sustainable way to ensure the continuous energy supply over time. It is important to ensure that the soil is not getting leached.

The real technical potential hence after the equations

$$\overline{P}_{techn} = \frac{E_{R\max}}{2 \cdot M_E} \cdot E_M$$

$$P_{techn} = \overline{P}_{techn} \cdot 0{,}88 \cdot A_D$$

results in 72.100 *kWh/(ha · a)* or 2.265 *TWh/a* when multiplied by the area of land that is technically available.

The technically realistic yield of energy provided by biomass should provide about 50% of the total energy consumption in Europe.

Humans themselves would be part of a closed CO_2 cycle (Figure 2.10). Excrement and/or waste are directed into a separator to separate solids and water. The water flows into a constructed wetland and is purified there to drinking water. The concentrated solid is converted into energy by being processed in an anaerobic reactor with a generator attached to it. The fermented residue is composted and used as a fertilizer for food plants. The constructed wetland may be run with water hyacinth and/or common duckweed which can be returned to the cycle.

Water hyacinths are fast-growing plants which should be cut quite frequently. In that way they are well suited to be utilized as an effective renewable source to provide biomass for energy supply.

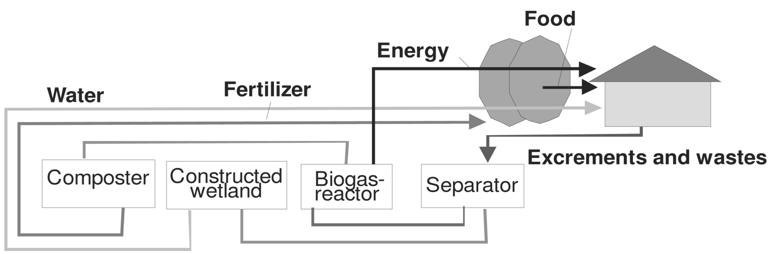

Figure 2.10 Closed CO_2 cycle.

2.4 Economic potential

Prices for crude oil and energy are rising globally. This trend anticipates that any technical feasibility will be profitable sooner or later.

The economic potential hence equals the technical potential

$$\overline{P}_{econ} = \frac{E_{R\max}}{2 \cdot M_E} \cdot E_M$$

giving 72.100 $kWh/(ha \cdot a)$. When multiplied by the area which is economically available

$$P_{econ} = \overline{P}_{econ} \cdot 0.56 \cdot A_D,$$

this results in 1.441 TWh/a, about 35% of the total primary energy supply of Germany.

2.5 Realizable potential

There is a huge gap between the technical and profitable potential and the realizable potential. A lot of what is technically feasible is rejected for various reasons, mainly special interests, e.g., landscape protection or job safety. A lot can be explained rationally but a lot is just based on emotion.

Today, almost 20 Mio ha of the agricultural area is cultivated only to produce food without considering the possibility of using it for energy supply. Just about 5% of the agricultural area (about 1.2 Mio ha) is disused. About 30% of this specific area is planted with energy-affording plants. In the next few years it may well be possible that the agricultural area used to produce biomass for energy supply will increase to about 2–2.6 Mio ha, even if we bear in mind that the forest area certainly cannot be simply transformed into an area of cultivable land for energy-affording plants. Such areas are expected only to deliver about 5 Mg/ha.a of dry biomass material.

In the same way, parks will remain on a long-term basis and may only provide a very small, almost negligible amount of biomass.

In the future, additional yield of biomass can only be achieved by exploiting those areas that are agriculturally used today. From a technology point of view, however, this is the only area that can be used to cultivate biomass or to provide output for the production of bio-diesel fuel. Today, about 70% of the non-food rape is consumed by the bio-diesel fuel industry. So just about 0.6 Mio ha are left and realizable for the cultivation of energy plants. The target of 4 Mio ha or about 20% of the total agicultural area in Germany available seems unrealistic and overestimated.[33)]

33) Cp. BOK 8

Further realizable potential may be provided by waste and sewage, which are already partly exploited in biogas plants. The fermentation of waste materials has to be seen in competition with being fed to animals, combusted, or composted (Table 2.9).[34)]

The potential to provide biogas is the most important data point and is specific to the kind of organic material used. For example, in Germany the materials shown in Figure 2.11 will be available by taking 2/3 of the entire volume of excrement (liquid manure) of the German agricultural livestock into consideration:

Table 2.9 Possibilities to exploit bio waste (– = not suited; 0 = partially suited; + = well suited).

	Feeding	*Combustion*	*Composting*	*Fermentation*
Liquid manure	–	–	0	+
Sewage sludge	–	0	0	0
Bio waste	–	–	0	+
Grass from lawns	0	–	+	+
Sewage from industry, biologically contaminated	+	–	0	+
Waste grease	–	–	–	+
Waste from slaughterhouse	–	–	0	+
Wood	–	+	+	–
Excrement	–	–	+	+
Straw	0	0	+	0

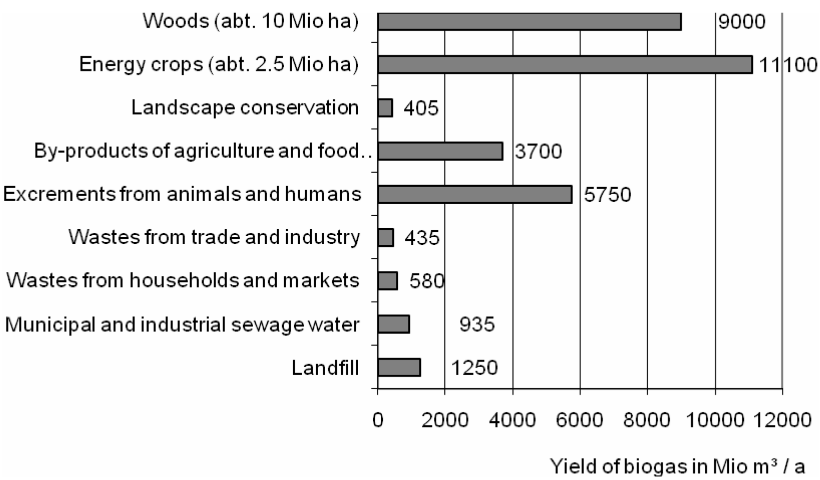

Figure 2.11 Yield of biogas from different sources[35)] in Mio m^3/a.

34) Cp. BOK 6

35) Cp. WEB 15

From these sources, the energy potential as to be seen in Table 2.10 can be derived:

190 Mio Mg of excrement may deliver the same yield as 500 000 ha of land to cultivate energy plants. The power generated by two power nuclear plants may be provided by fully exploiting agriculture and forestry.[36)]

Another source of energy is fermented plants of created wetlands, which deliver a much lower but still appreciable amount of biomass, or the wastewater from the paper industry.

Even human urine may be exploited (Figure 2.12). Around 40 Mio Mg a^{-1} of urine (500 L/person.a)[37)] could be made available by investing in changing the complete system of sewage disposal; so-called "gray water" from private households, e.g., from washing dishes, laundry, or bathing, should be separated from brown water (containing excrement) and urine. Even the toilet flushing would need to be omitted to avoid too much dilution. A potential solution may look as shown in Figure 1.16.

The importance of input from landfills will decrease in the next few years. Legal regulations and restrictions have become much stricter, which may finally render this source unprofitable.

Table 2.10 Potential of energy from biogas from different sources.

Sources for biogas production	***Energy potential [TWh a^{-1}]***
Landfill	6
Communal and industrial sewage water	
Organic wastes from households and markets	18
Organic wastes from industry	
Excrement (190 Mio Mg a^{-1})	
Byproducts of agriculture and food production	47
Material from landscape conservation	
Plantations of energy plants (area ca. 2.5 Mio ha) (15 Mg/ha.a)	141
Wood (10 Mio ha forest area) (5 Mg/ha.a)	187
Urine	4
Nutrition in sewage water	5
Total	408

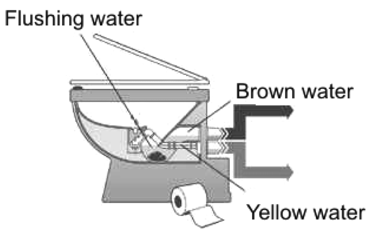

Figure 2.12 Separation of human excrements.[38)]

36) Cp. BOK 7
37) Cp. WEB 70
38) Cp. WEB 60

Overall, the biggest output of energy from renewable resources, however, will be provided by using bio waste from the food industry. Pomace, for example, from wine making, consists of grape pods, stones, and stems, which can be used for energy recovery. Today pomace serves as a base for the production of alcohol and/or as animal feed, as does the waste from breweries, sugar refineries, and fruit processing plants. All this bio waste can be a source of profit by fermentation. Even the wastewater from dairies or waste from slaughterhouses will be fermented in the future. The potential is huge. Annually 0.9 Mio sheep and horses, 3.8 Mio cows, 0.4 Mio calves, and 43 Mio pigs are slaughtered in Germany.

The total yield of realizable biogas sources in Germany should be around 408 TWh a^{-1}, which is about 10% of today's primary energy supply and about 48.5% of today's primary energy consumption of natural gases (natural gas, mine gas, sewage gas) – about 840 TWh a^{-1}.

When all biogas is used to generate electrical power, the potential yield of power from the biogas amounts to about 143 TWh a^{-1}, assuming an efficiency of 35% for the power generators. Biogas may hence contribute to 10–12% of the total power supply.[39)]

In some literature, lower yields of biogas of around maximum 74 TWh a^{-1}[40)] only are estimated.

In Western Europe, France and Germany are leading just looking at the potential yield of energy resulting from cultivating energy-affording plants and exploiting agricultural by-products. France has the highest potential with 178 TWh a^{-1} (Figure 3.1).

This means that so called "passive houses", with a very low energy requirement for heating (primary energy consumption of 120 kWh/m^2.a), can be heated by using biogas, e.g., by generating power by a fuel cell. The required amount of energy will be supplyable by animals. One animal unit (abbreviation used: GVE) 500 kg in weight produces 550 m^3 biogas per year or, depending on the energy content of the biogas, ca. 3500 kWh_{th}. One cow can hence supply a small apartment of about 30–60 m^2 living area with enough heat. Or a passive house of about 400–800 m^2, needing ca. 40 000 kWh_{th} a^{-1}, can be heated with energy plants growing on one ha of field.

39) Cp. BRO 6

40) Cp. BOK 63

3
History and status to date in Europe

Very old sources indicate that using wastewater and so-called renewable resources for the energy supply is not new, but was already known before the birth of Christ.

Even around 3000 BC the Sumerians practiced the anaerobic cleansing of waste.

The Roman scholar Pliny described around 50 BC some glimmering lights appearing underneath the surface of swamps.

In 1776 Alessandro Volta personally collected gas from the Lake Como to examine it. His findings showed that the formation of the gas depends on a fermentation process and that the gas may form an explosive mixture with air.

The English physicist Faraday also performed some experiments with marsh gas and identified hydrocarbon as part of the it. A little later, around the year 1800, Dalton, Henry, and Davy first described the chemical structure of methane. The final chemical structure of methane (CH_4), however, was first elucilated by Avogadro in 1821.

In the second half of the 19th century, more systematic and scientific in-depth research was started in France to better understand the process of anaerobic fermentation. The objective was simply to suppress the bad odor released by wastewater pools. During their investigations, researchers detected some of the microorganisms which today are known to be essential for the fermentation process. It was Béchamp who identified in 1868 that a mixed population of microorganisms is required to convert ethanol into methane, since several end products were formed during the fermentation process, depending on the substrate.

In 1876, Herter reported that acetate, found in wastewater, stoichiometrically forms methane and carbon dioxid in equal amounts. Louis Pasteur tried in 1884 to produce biogas from horse dung collected from Paris roads. Together with his student Gavon he managed to produce 100 L methane from 1 m^3 dung fermented at 35 °C. Pasteur claimed that this production rate should be sufficient to cover the energy requirements for the street lighting of Paris. The application of energy from renewable resources started from that time on.

Biogas from Waste and Renewable Resources. An Introduction.
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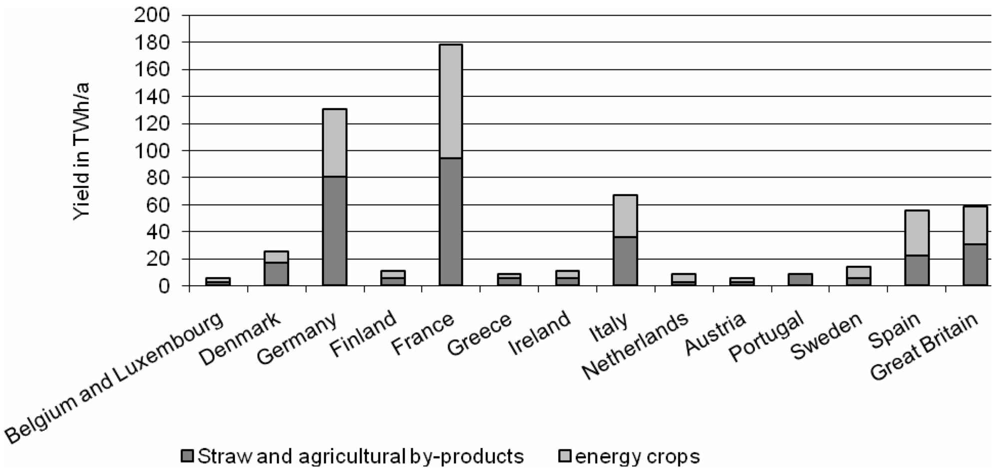

Figure 3.1 Biogas production across European countries.

3.1
First attempts at using biogas

While Pasteur produced energy from horse dung, in 1897 the street lamps of Exeter started running on gas from waste water. This development suggested that more and more biogas could be produced by anaerobic purification plants for wastewater. Most of the biogas, however, was still wasted to the atmosphere.

In 1904 Travis tried to implement a two-step process which combined the purification of waste water with the production of methane.

In 1906 Sohngen accumulated acetate in a two-step process. He found that methane was formed from three basic materials: formate plus hydrogen plus carbon dioxide.

In 1906 the technician Imhoff started constructing anaerobic waste water treatment units in the Ruhr, Germany. He installed so-called “Imhoff tank” (Figure 3.2) with separate spaces for sedimentation and digestion. The residence time of the bio waste was 60 days.

In Germany methane gas was first sold to the public gas works in the year 1923.[41)] In the next years this practise became more and more common in Europe. A further development was the installation of a CHP near the biogas production and to produce the current necessary for the waste water treatment plant and to heat houses with the excess heat from the CHP.

Until the 2nd world war, the use of biogas was progressing very fast and much effort went into developing more efficient systems, e.g., floating-bell gasholders, efficient mixers, and heating systems to increase the yield of digestion. In Europe, highly technical spherical digestors agitated with intermittent vertical screw

41) Cp. JOU 15

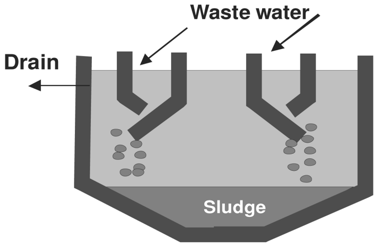

Figure 3.2 Imhoff tank – a sedimentation tank for the mechanical sewage treatment.

conveyors and a haul-off in the cover was preferred. In the United States, simple cylindrical vessels were used with flat bottoms, continuously circulating mixing systems, and collecting pipes at the top.

Around 1930 it was first tried to remove water, carbon dioxide, and sulfide from the biogas, to compress it in gas bottles, and to use it as fuel for automobiles. In order to maximize the efficiency of such a procedure, so-called co-fermenters, i.e. solid organic waste, e.g., food, cereals, and silage were added. Different combinations were tried, but only in 1949 (Stuttgart) the addition of fat after fat separation enabled the yield of biogas to be increased.

In Halle, experiments on digestion were performed by adding waste liquorice, rumen, lignin and/or cereals. Lignin was the least efficient material, providing 19 L gas per kg dry matter with a dwell period of only 20 days. Rumen provided $158\,L\,kg^{-1}$, liquorice even $365\,L\,kg^{-1}$ but with a dwell period of 45 days. Around 1950 Poebel conducted some extensive research on co-fermentation in the Netherlands by including organic waste of households in his experiments.

Around the same time (1930–1940) the idea came up to use agricultural waste to produce biogas. Buswell's target was to provide the whole amount of gas consumed by Urbana, a small city in Illinois. He examined many different natural materials. In parallel, Ducellier and Isman started building simple biogas machines in Algeria to supply small farmhouses with energy. This idea was brought to France, and many people installed their own small and technically very simple biogas plants.

Around 1945, only Germany started using agricultural products to produce biogas. Imhoff again was leading. In 1947 he claimed that the excrement of one cow delivered 100 times more biogas than the sewage sludge of one single urban inhabitant. He projected how much biogas the excrement of cows, horses, pigs, and potato haulms would supply. The first small biogas plant with a horizontal cylindrical vessel for fermentation was developed in Darmstadt, and in 1950 the first larger biogas plant was inaugurated in Celle. In total, about 50 plants were installed during the following years in Germany.

While expanding the number of biogas plants, globally researchers deepened their knowledge about the chemical and microbial processes contributing to fermentation. Doing very fundamental biochemical research in 1950, Barker detected the methane-forming bacteria *Methanosarcina* and *Formicicum methanobacterium*. Very important also was the finding from Bryant et al. in 1967 showing that methane-forming microbial cultures consisted of a minimum of two kinds of bacteria. One type was said to be responsible for converting ethanol to acetate and hydrogen, and the other for forming methane via chemical reaction of carbon dioxide and the free hydrogen. Today it is known that four specific and different kinds of bacteria must work in synergy to produce biogas.

Around 1955 the importance of biogas was significantly reduced, as biogas was not profitable any longer due to an excess of oil. The price of fuel oil was very low, ca. 0.10 L^{-1}. At the same time, more mineral fertilizer was used in mass. Almost all the biogas plants were shut down except two: that in Reusch/Hohenstein (1959) and the Schmidt-Eggersgluess plants close to the monastery of Benediktbeuren, built around 1955.

This plant, consisting of two digesters, one storage tank, a gasholder, and the turbine house, was originally constructed for 112 animal units (GVE) and a gas production of 86 400 $m^3 a^{-1}$. In the last few years, however, it was only used for about 55 GVE. The plant cost was 72 000 US$ but it has cost around 12 000 US$ for maintainance annually during the past 25 years. The ratio of straw chaff to the excrement and urine was 1 : 2. The dung was flushed into a dump, mixed with anaerobic sludge, and pumped daily into the digestors. The principle of the "change container" procedure is that while the material digested in the first fully filled fermenter for ca. 20 days, the second was filled. If the second container was full, the content of the first digestor was transferred into the storage tanks. In that way the first digestor was refilled while material was digesting in the second container.

Temperatures of 38–39 °C were considered as optimal for the digestion. The resulting biogas was used in the monastery kitchen for cooking. Any surplus was connected to a 70-HP MAN diesel engine. In the end, however, the plant was shut down in 1979 when cattle breeding was abandoned.

3.2
Second attempts at using biogas

In 1970 the demand for biogas increased, driven by the oil crisis. The number of facilities went up to 15 in Bavaria and up to 10 in Baden-Wuerttemberg.

Later, in the 1990s, biogas technology was stimulated for two reasons:

- The profitability of using power derived of biogas
- The recycling management and Waste Avoidance and Management Act which was implemented in 1994 and resulted in higher costs for disposal of solid waste.

The agricultural sector observed the trend and accepted it very conditionally, since the biogas facilities did not work in a profitable way, mainly because of the high costs in constructing the facilities. Only after the farmers had learned to work themselves and to pool their experience were the facilities run economically.

Table 3.1 Number and total amount of digested material of large fermentation and co-fermentation biogas plants of bio waste (>2500 $Mg\,a^{-1}$) in Europe in 1997.[42]

	Number of biogas plants	*Mg of digested waste per year*
Austria	10	90 000
Belgium	2	47 000
Denmark	22	1 396 000
Finland	1	15 000
France	1	85 000
Germany	39	1 081 700
Italy	6	772 000
Netherlands	4	122 000
Poland	1	50 000
Spain	1	113 500
Sweden	9	341 000
Switzerland	10	76 500
England	1	40 000
Ukraine	1	12 000
Total	108	4 241 700

In 1954, Ross, in Richmond, USA, reported about the process of digesting communal waste with sludge. Apparently, a closed facility was running in Chicago, USA, to digest the waste.

At the end of the 1990s, numerous plants were built and implemented for the mechanical-biological treatment of garbage. The technology was based on anaerobic with some aerobic composting. The aerobic process proved to be advantageous, since it enabled enough energy to be provided to run the plant itself.

Not only Germany but other European countries applied the same technology for the disposal of waste (Table 3.1). For example, in Denmark several large biological gas facilities were built for processing of liquid manure together with residues from the food industry.

About 44 anaerobic fermentation plants with a capacity of about 1.2 Mio Mg bio waste in total existed in Germany in April 1999. Of these plants, 31 were running by the wet-fermentation procedure (18 single-stage, 13 multi-stage procedures); the other 13 facilities worked according to the dry-fermentation process (9 single-step, 4 multi-level procedures). At the same time, around 550 aerobic bio waste composting plants were functioning, with an overall capacity of approximately 7.2 Mio Mg bio waste.[43]

42) Cp. BOK 22

43) Cp. WEB 46

3.3
Third attempts at applying biogas

In 2000, the law of "Renewable Energies", which stated the rules for the subsidization of the power supplied by biogas facilities, became effective. Over the past few years, the number of biogas facilities has continuously been rising, especially after implementing even higher subsidies. About 1500 biogas facilities were in use in Germany, most of them in Bavaria.

Electrical power was supplied from biogas into the network out of the sources shown in Table 3.2.

3.4
Status to date and perspective in Europe

In the year 2005 in Austria a biogas plant were constructed to feed $10\,m^3\,h^{-1}$ crude biogas (giving to $6\,m^3\,h^{-1}$ clean biogas) into the natural gas network, equivalent to $400\,MWh\,a^{-1}$.[44] The gas is produced from the excrement of ca. 9000 laying hens, 1500 poultry, and 50 pigs. In Sweden, communal vehicle fleets and even a train are running on biogas.[45]

In Germany, the number of biogas plants has increased during the past few years following a governmental promotion handed out for the installation of plants. In fact the number was tripled from 850 plants connected to the electricity network in 1999 to 2700 plants to date in 2006 (Figure 3.3). In the agricultural sector alone, more than 600 plants were put on stream in 2006, contributing to a total power output of 665 MW and a total energy generation of 3.2 TWh provided by all biogas plants. It is planned to construct 43 000 biogas plants in Germany until the year 2020.

Almost all waste water is already fed into central sewage water treatment plants area-wide with facilities to produce sewage gas. Several small plants with a volume of waste water of less than $8\,m^3$ per day still exist. The objective is, however, to integrate these, too, into the central system as soon as the appropriate pipework is installed.

Table 3.2 Electric power supply from biomass in Germany in the year 2000.

	Number	*Installed electric power [MW]*	*1000 MWh a⁻¹*
Sewage gas	217	85	61
Landfill gas	268	227	612
Biogas	1040	407	127
Total	1525	407	800

44) Cp. WEB 93

45) Cp. WEB 94

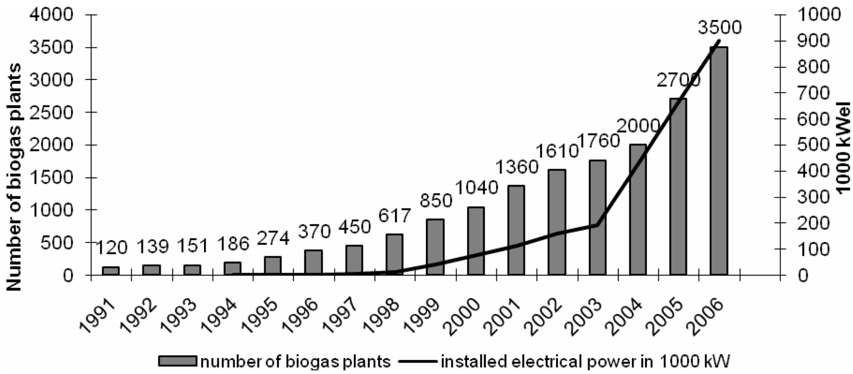

Figure 3.3 Expansion of biogas production in Germany.[46]

Overall, the agricultural sector is seen to be a rich source of biomass. Projections suggest that the agricultural waste alone will enable more than 220 000 additional individual plants and communal facilities to be run, provided that an investment of 25–40 bn US$ is allocated. This will provide farmers the opportunity to become more independent from the food trade and get additional incomes working as "energy farmers".

For example, in Hungary in December 2005 a biogas plant with a capacity of 2.5 MW was inaugurated. The plant is fed with liquid manure from several cattle farms and wastes from poultry farming.

46) Cp. WEB 95

4
History and status to date in other countries

In the rich industralized countries, biomass represents on average about 3% of the total amount of primary energy carriers. In the emerging markets it accounts for 38%. In some particularly poor countries it reaches even more than 90%.

In the United States, the percentage of biomass related to the total consumption of primary energy is about 4%, in Finland it is 2%, in Sweden 15%, and in Austria 13–15%.[47),48)] In contrast, Nepal, a developing country, has 145 000 biogas plants for a population of about 20 Mio with ca. 9 Mio cows and ca. 7 Mio other useful animals. It is hence the country with the highest number of biogas plants per inhabitant. The number is expected to increase by another 83 500 plants, financed through the world bank. In Vietnam, ca. 18 000 biogas plants were built by the year 2005 and another 150 000 are planned to be constructed by 2010.[49)] Similar projections are available for India and China. The financing could be managed through the sales of CERs (certified emission reductions),[50)] because methane mitigation saves carbon emissions and can be traded as carbon credits.

In the years around 10 BC, biogas was first used in Assyria for heating baths. Little information is available about later years. But, as early as 1859, a hospital for leprosy patients in Mumbai, India, inaugurated their purification plant for waste water to provide biogas for lighting and to assure power supply in case of emergencies. At the end of the 19th century the first biogas plants were constructed in southern China. Here, Guorui developed a digester of 8 m^3 capacity in the year 1920 and founded the Sanzou Guorui Biogas Lamp Company. He moved to Shanghai in the year 1932 and named his new enterprise Chinese Guorui Biogas Company, with many subsidaries in the south of China. Also, in the region of Wuchang, the building of biogas plants was started in order to solve the problems of disposal of liquid manure and improve hygiene.[51)] In India Jashu Bhai J Patel developed a floating cup bioreactor in the year 1956, known as “Gobar Gas plant” 1962 this construction were acknowledged by the “Khadi and Village Industries Commission (KVIC) of India” and distributed worldwide. Only in the 80th this construction were replaced by the Chinese “dome” bioreactor.

47) Cp. WEB 89
48) Cp. BOK 2
49) Cp. WEB 96
50) Cp. WEB 97
51) Cp. WEB 98

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In Africa, 64 Mio ha of forest was cut between the years 1990 and 2005 for fuel. One biogas plant with a 10 m^3 bioreactor could lead to the reforesting of 0.26–4 ha of land.

4.1 History and status to date in China

In China, the consumption of primary energy is about 11 500 TWh per year today and is expected to double[52] within the next 20 years, given the strong development of the country, especially in the more rural areas, where 70% of the population live and 40% of primary energy is required. The use of biomass as the primary energy carrier is considered to be very important as to be seen in Figure 4.1. Already, in the year 2001, waste water from different industries, e.g., the alcohol, sugar, food, pharmaceuticals, paper industries, and even slaughterhouses was fermented in biogas plants. 600 plants with reactor volumes of 1.5 m^3 were running, with a total capacity of 150 Mio m^3 for waste disposal, generating about 1 bn m^3 of biogas.

The yield of biogas in China in the future is estimated to be much higher. Some projections give the total annual realizable potential of biogas as 145 billion m^3,[53] providing about 950 TWh. Other calculations[54] foresee 250 TWh (Table 4.1) only from agricultural residuals as a main source. In this assumption, industrial sewage water, communal wastes, and energy plants were not considered.

Given the long history and experience in the field of biogas technology in China, the growth figures only reflect a continued effort in driving any progress in this sector, which started a very long time ago.

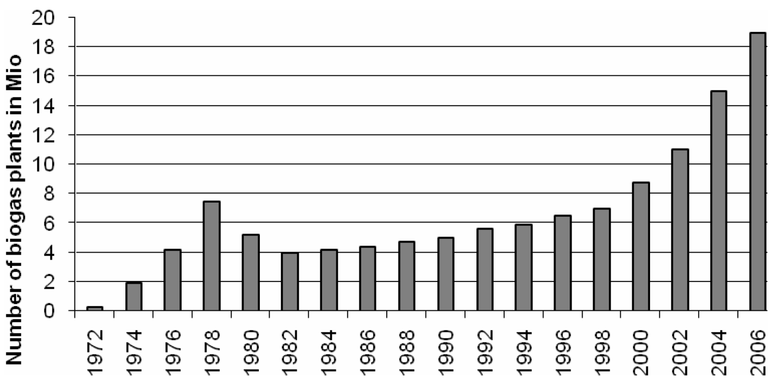

Figure 4.1 Expansion of biogas facilities in China in Mio.

52) Cp. BOK 64

53) Cp. WEB 99

54) Cp. DIS 7

Table 4.1 Potential for biogas production in China.

	TWh
Excrement	20
Residuals from agriculture	200
Residuals from forestry	30
Total	250

4.1.1 Period from 1970 to 1983

In the years around 1970, the first wave of installations of small self-made biogas plants started in China. These so-called "power plants at home" were attached to private rural houses. The costs for such constructions were quite significant. On average it took 17 working days for construction and a family had to invest around 5% of their annual income. But within only a few years the investment was amortized by savings on fuel costs and some additional income from selling the fermented residues as fertilizer.

About 6 Mio biogas plants were set up in China, promoted by the Chinese government to provide energy, for environmental protection, and to give an improvement in hygiene. The "China dome" bioreactor became a standard construction (see Part V) and an example for other developing countries. Such a typical plant consisted of a concreted pit of a few cubic meters volume.[55] The raw materials – feces, wastes from the pig fattening, and plant residuals – were introduced via a gastight inlet into the interior of the reactor. The gas resulting from fermentation collected in the storage space above the substrate. Whenever needed, a slight overpressure was applied to direct some of the gas via hoses to the kitchen. The biogas was usually not used for power supply. This practice was quite common, and about 7 Mio households, about 6% of all the households in the country, were applying this principle in 1978.

The plants were usually integrated in productive agricultural units, i.e. cooperatives (Figure 4.2). Only a few of these had their own power plant supplied by biogas.

In a cooperative, about 90 families lived together. They cultivated sugar cane and bananas, carried on freshwater fishing, and bred silkworm. Any waste was collected and brought to a central biogas plant of 200 m^3 volume, where it was transformed into fuel. The fuel was used for cooking, to heat the living rooms, and to drive electrical generators. At the same time, the process in the biogas plant killed the germs in the feces, leaving a hygienic residue for use as fertilizer. The people suffered less from parasitic infections and the nutritional value of the soils was improved, yielding large crops. The cooperative society was able to survive on

55) Cp. BOK 11

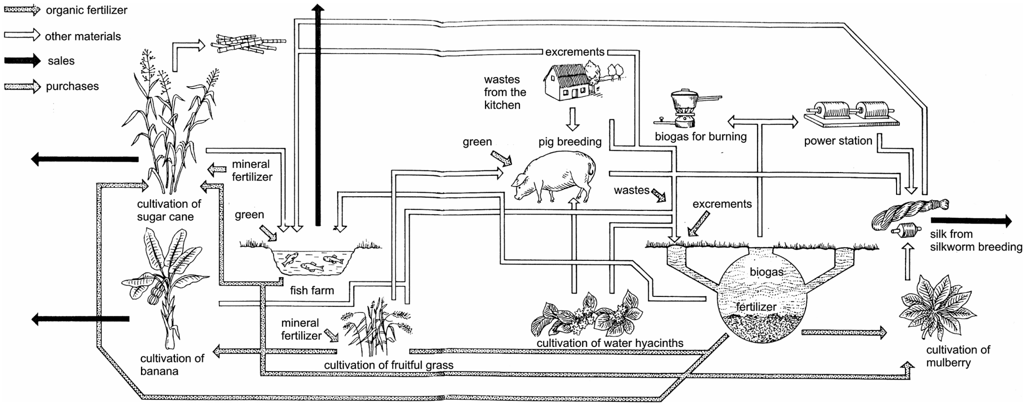

Figure 4.2 Autarc system in developing countries.

its own and only imported a few small amounts of grass for feeding, some chemical fertilizer, and some liquid manure from the neighborhood.

From a political and economic point of view, however, there was no pressure to continue making progress in this field. The importance and interest declined at the end of the period (around 1983), and more and more biogas plants were shut down.

4.1.2 Period from 1984 to 1991

During this period, quite a few new plants were installed, while about the same number of old plants were shut down. The biogas technology, however, gained again more importance since universities started to be engaged in the recovery of biogas and acquired new insights and knowledge.

4.1.3 Period from 1992 to 1998

Building on the new results of the latest research, more biogas plants were set up again, starting in the year 1992. This vogue was supported by the following three political slogans and campaigns:

4.1.3.1 "A pit with three rebuildings"

The campaign named "A pit with three rebuildings", encouraged people to build a pit serving as a bioreactor and to rebuild three rooms: the sty, the toilet facilities, and the kitchen.

The sty and the toilet room were rebuilt to have direct drainage into the 8–10 m^3 bioreactor. The kitchen was set up with a biogas cooker directly connected with suitable pipework to the bioreactor. The toilet water for rinsing was withdrawn from the top of the reactor using a scoop.

4.1.3.2 **“4 in 1”**

Especially in the north of China, the campaign named “4 in 1” was strongly accepted as it was based on a concept that was developed in a small city, Pulandian,[56)] in the province Liaoning. This concept took into account the continental climate in the north of China, where there are huge temperature differences between summer and winter. The significant temperature drop and the cold climate during winter only allowed the common biogas plant to be run for about 5 months.

In order to operate the plant during the whole year, the following four different sections were built:

- Bioreactor with a volume of about 8 m^3
- Greenhouse with about 300–600 m^2 of space
- Sty with about 20 m^2 of space
- Toilet.

The yield of biogas was about 0.15 to 0.25 m^3 per cubic meter of reactor volume. A volume of 8 m^3 for the bioreactor was sufficient to produce enough gas for a family of 4 members. The fermented residue from the reactor was used as a fertilizer in the greenhouse, while the biogas itself was used for cooking and to heat and light the greenhouse. Overall, the investment for such a plant and concept was usually recovered after 1–2 years.

4.1.3.3 **“Pig-biogas-fruits”**

The campaign named “Pig-biogas-fruits” was strong in the south of China. This plant, which the government promoted,was similar to the “4 in 1” concept, but, because of the milder temperatures, it was not mandatory to have all the different sections consolidated together. Further, the greenhouse was not required, and the fertilizer was used for fruit trees.

4.1.4
Period from the year 1999 onwards

In the year 1999, the following two projects were established to fight against the worsening environmental crisis: “Energy and environment” and “Home-bio and wellbeing”. Similarly to the actions taken in Germany the programs included financial aid to motivate people in the rural areas of China to build biogas plants. The concept is working and the number of plants is rapidly increasing.

In the year 2003, “China’s 2003–2010 National Rural Biogas Construction Plan” was announced. Objectives were set aimed at increasing the number of biogas plants in China to 20 Mio by 2005, giving 10% of all farmers’ households the use of their own biogas plant, and to 50 Mio by the year 2010. Each small biogas plant earns an award of 150 US$ from the government. China plans to supply 15% of its total energy consumption from renewable resources by the year 2020, which means that 200 Mio biogas plants have to be built. An investment of 187 bn US$ is foreseen.

56) Cp. WEB 100

Near the city of Meili in the province of Zhejiang, biogas is produced from the excrement of 28 000 pigs, 10 000 ducks, 1 000 000 chickens, and 100 000 hens. In Mianzhu in the province Sichuan a biogas plant closely connected to an ethanol production plant produces some MW electricity from biogas.

Nanyang in the province Henan is one of the leading biogas cities in the world because of its location in the center of a rank soil area. Here, there is an abundance of corn, and 1.75 Mio Mg cereals of second quality can be used for the production of biogas.[57)]

4.2 History and status to date in India

India's[58)] consumption of energy today is at 6500 TWh a^{-1}, but this is expected to double in the near future. Today, about 2.5 Mio biogas plants are running, with an average size of 3–10 m^3 of digester volume. Depending on the substrate, the plants generate 3–10 m^3 biogas per day, enough to supply an average farmer family with energy for cooking, heating, and lighting.

The national advisory board for energy in India has published a report forecasting the required quantity and the manner of supply of energy in the future. The board estimates that India has enough resources to sustain 16–22 Mio small biogas plants with 2 m^2 reactor volumes, each to supply sufficient energy for a farmer family with 4 cows. The estimates suggest that the plants will together provide an energy yield that corresponds to 13.4 Mio Mg of kerosene oil. The amount of fertilizer is projected at 4.4 Mio Mg.

In plants in India, the substrate, cattle dung, and biogenous waste, are manually mixed with water in a ratio of 10% dry matter to 90% water. The mix is filled into the digester by simply pushing. The reactor is neither heated nor isolated, enabling the fermentation process to take place at temperatures in the the region of 14 °C during winter and 25 °C during summer. In the reactor itself, the substrate is mixed by a simple mixer which is operated manually. After a dwell time of the substrate in the reactor of around 100 days the fermented residue is removed with buckets or scoops. Pumping systems are not used.

In general, such a small biogas plant costs around 5000 Indian rupees (about 120 US$) per cubic meter of digester. The plants are constructed with the help of local artisans who receive a daily wage of 50 rupees (1.20 US$).

The construction of more and more biogas plants has revealed several beneficial side effects, such as a significant reduction in the exhaustive cultivation of forests. Unexpected successes were noted in the medical sector also. Since respiratory systems and eyes were no longer exposed to aggressive wood smoke from fires, the number of cases of acute asthma and eye diseases was significantly reduced.

Overall, the use of biogas for energy supply provides economic but also ecological and hygienic advantages.

57) Cp. WEB 98

58) Cp. WEB 13

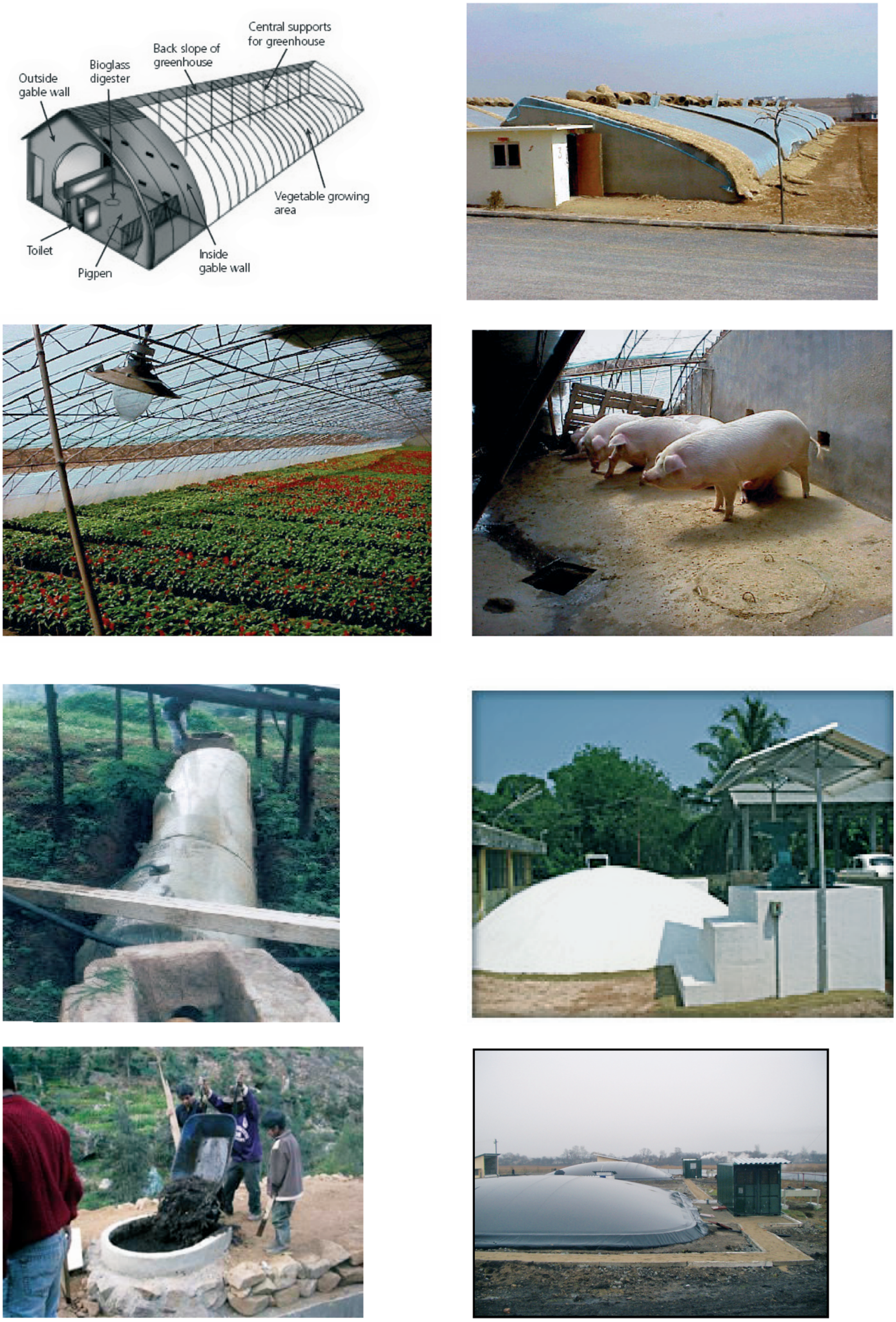

Figure 4.3 Biogas plants.
China: cross section of a "four in one" plant in China (1st row, left), "Four in one" plant in China (1st row, right)
Green house in China, part of a "Four in one" plant (2nd row, left), pig pen with loophole to digester and digester cover in the floor (2nd row, right)
Plastic biogas reactor in South Africa (3rd row, left), Moderm biogas plant in Kerala, India, (Suntechnics GmbH) producing 6.75 kW to lighten street-lamps (3rd row, right), Feeding of a biogas plant in Peru (4th row, left), Bioreactors in the Ukraine (Elenovka/ Dnipropetrovsk).

4.3 Status to date in Latin America

In countries in Latin America, e.g., Argentina, Peru, Brazil, Chile, and Mexico, the implementation of biogas plants is just starting. The simple constructions are similar to those in Asia, with a reactor volume of 2–10 m^3 Instruction manuals can be found on the Internet.[59)]

4.4 Status to date in the CIS states

In the CIS states, energy was available in abundance over many years. This changed only very recently. Following attempts to adapt the price of oil and gas to world prices, energy prices have already risen considerably regionally and will raise drastically (by a factor of 5) within the next few years.[60)] People can no longer afford to heat with fossil sources of energy, and politicians are moving only very slowly toward regenerative sources of energy.

In Russia, the company "AO Stroijtechnika Tulskij Sawod" in Tula has been offering two standardized small plants for the production of biogas from domestic waste since the year 1992.[61)] One plant, with a bioreactor volume of 2.2 m^3, processes 200 $kg\,d^{-1}$ substrate. This can be the excrement from 2–6 cows, 20–60 small domestic animals and pigs, or 200–600 head of poultry, and can also include plant material, straw, corn, sunflowers, and leftovers. The other plant consists of two bioreactors of 5 m^3 volume each, in which fermentation takes place at a temperature of 55 °C, and a biogasholder with a volume of 12 m^3. Thus, up to 80 KWh of electrical power is produced per day. The plants can be transported by truck to the place of installation. Optionally provided can be a generator, a heating system, or an infrared emitter. Because of the cold winters in Russia, the plants are provided with particularly thick thermal insulation.

Up to now, more than 70 plants have been installed in Russia, more than 30 in Kazakhstan, and 1 plant in the Ukraine.

In the Ukraine, 162 000 m^3 volume of bioreactors were formerly installed in sewage treatment plants, but because of their poor condition, these have had to be shut down. However, there are new plans to produce ca. 5000 m^3 biogas equal to 28.2 TWh from animal husbandry and poultry farming (47%), sewage sludge (6%) and landfills (47%).[62)] In the Ukraine, an additional 2–3% of the agricultural land can easily be used for the production of biogas. About 3000 biogas plants would have to be built for this purpose. Thus, the Ukraine could become independent of imports of natural gas.

A first plant was erected in 2003 at a pig-fattening station in the village Eleniwka in the province of Dnipropetrovsk. It supplies 3300 m^3 biogas daily. The invest-

59) Cp. WEB 101
60) Cp. WEB 102
61) Cp. WEB 103
62) Cp. WEB 104

ment costs of 413 300 US$ were financed by a Netherlands investor. The power is sold. It is estimated that the break-even point will be reached within ca. 8 years.

Presently, some similar plants are under construction or planned in the Ukraine. The Bortnichi sewage treatment plant is planned to provide the capital Kiev with 9 MW, ca. 10% of the total electrical power consumption. An Austrian company will perhaps fund the investment costs of 10 Mio US$. Break even is foreseen within 2.5 years.

5
General aspects of the recovery of biomass in the future

In developed countries it is difficult for an agriculturist to decide how to best use his land.

If the object is to use the land in the best ecological way possible, a slow downcycling of the biomass will be recommended in the first place. The agriculturist should decide to do silviculture. For example, wood can be used to build houses. After the house has been deconstructed, the quality of the wood is still good enough to serve as material for wardrobes or rail tracks and then to make boxes or art works. Only after such a long cycle should the wood be combusted.

If the object is to use the land in the best economic way possible, the financial aid of governmental institutions will be particularly considered. Depending on the institutional programs, it may well be most profitable to cultivate energy plants to produce biodiesel or ethanol. But maybe it will be most efficient even to have the agricultural area lying idle, as the government may have assigned higher financial benefits to it as if it was used to cultivate, e.g., food plants.

If the agricultural area is to be used to maximize the yield of renewable energy, a combination of different technologies will be most efficient, e.g., wind turbines installed to generate electricity, with photovoltaic cells underneath and the cultivation of grass or energy-affording plants at an even lower level (Figure 5.1). The

Figure 5.1 Wind-driven generator, photovoltaic and energy crops.

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cultivation of two different energy-affording plants in sequence is most profitable. If liquid manure is available, the biomass is recommended to be fermented in a biogas plant; otherwise it is to be combusted.

If the yield of fuel is to be maximized, it is recommended that starch-based plants rather than fat-containing plants should be cultivated to minimize the loss of energy during transformation processes.

Biomass in general will achieve much greater importance as a primary carrier for energy supply in the near future. This will lead to significant changes in the personal habits of people and in the agricultural cultivation methods applied today. Humankind is almost forced to face those changes given the fact that resources of fossil energy carriers are running short. It may be possible in the remote future to meet the energy demand by using biomass only.

It is highly critical that the developed markets should adjust to the required changes as quickly as possible. The emerging markets, in contrast, should not imitate the developed markets, but must take different approaches immediately to recover and secure the supply of energy.