Politecnico di Milano

Diplomarbeit

Technological issues and modelization of biomass driers

Ausgeführt zum Zweck der Erlangung
des akademischen Grades eines Diplom-Ingenieurs
für Verfahrenstechnik
unter der Leitung von

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Wien, am 2007 Unterschrift

Acknowledgement

I would like to express my sincere thanks to all who have contributed to this work. Greatly, I acknowledge the coaching, the valuable suggestions and the scientific support of Prof. Stefan Consonni from Politecnico di Milano, who made it possible for me to write this diploma thesis in Italy.
Further, I would like to thank Univ. Prof. Hermann Hofbauer for his scientific support, valuable suggestions and assistance when I returned to Vienna.

I would also like to thank Annamaria Conti and Alessandra Ciprandi for their help to accomplish some administrative barriers in Italy.

Thanks are also due to Sandra Beneder for proof reading my thesis.

I am grateful to my parents, who have given me financial and emotional support during all the time of this work and allowed me to acquire a broad educational basis.

Kurzfassung

Man kann Pflanzen als Energiespeicher betrachten, da die Sonnenstrahlen von ihnen absorbieren, umgewandelt und in chemischer Form gespeichert werden. Die Umwandlungseffizienz der Pflanzen ist oft abhängig von der Klimazone. Damit Biomasse konkurrenzfähig zu Kohle, Gas oder Öl ist, müssen die Erträge pro Hektar gesteigert werden, indem zum Beispiel schnell wachsende Pflanze gezüchtet werden, oder eine Beeinflussung der Photosynthese durch Genmanipulation stattfindet. Ein Vergleich der landwirtschaftlichen Nutzung für den Anbau von Energiepflanzen und normaler Landwirtschaft zeigt, in Bezug auf die Wirtschaftlichkeit, ob ein Umstieg rentabel ist.

Zu steigender Konkurrenzfähigkeit der Biomasse tragen neue Verfahren und höhere Effizienz der Umwandlungsanlagen bei. Eine Auflistung der Verfahren die es ermöglichen Biomasse in Wärme, Elektrizität oder flüssige Stoffe umzuwandeln, zeigt welche Biomasse für welchen Zweck am Geeignetesten ist.

Der Vergleich der Biomasse mit anderen erneuerbaren Energiequellen wie Photovoltaik, Windenergie oder der Solarwärme zeigt ihre momentane maximale Effizienz, sowie die Kosten für solche Anlagen und Zukunftsperspektiven der einzelnen Bereiche.

Die Charakterisierung der wichtigsten Parameter für die Holzqualität zeigt, was getan werden muss um eine optimale Prozessführung zu gewährleisten. Bei der Anlieferung verfügt das Holz nicht über die benötigten Eigenschaften für die Vergasung, insbesonders ist die Feuchtigkeit des Holzes ein Problemfaktor. Ein Vergleich zwischen den einzelnen Trocknungsanlagen zeigt, welche sich am Besten für die nachfolgende Holzvergasung eignen würde.

Ein vereinfachtes mathematisches Model eines Drehrohrtrockners beschreibt, das Verhalten des Trocknungs-Mediums und der Biomasse, am Eingang und Ausgang der Anlage. Dadurch soll eine Hilfstellung, zur Entscheidungen in Bezug auf die richtige Wahl der Trockneranlage, gegeben werden. Durch Internetrecherchen wurde am internationalen Markt nach Produzenten gesucht, welche Informationen über möglichen Faktoren die einen Einfluss auf die Größe, Funktionalität und die Kosten eines Trockners haben, und diese dann zur Verfügung stellten.

Abstract

Sun energy that hits the earth's surface can be stored in different ways, namely by the evaporation of water, through air heating causing air movements or by plants converting sun energy into a chemical form by means of photosynthesis.
There is a big gap between the maximum theoretical photosynthesis efficiency of plants and their actual efficiency achieved under normal conditions. In order to make biomass more competitive to fossil energy, its yield per hectare has to rise, for instance through breeding of fast growing plants or the genetic manipulation of photosynthesis. Biomass and therefore stored chemical energy can be dissipated into heat, electricity or liquid products through either a thermo-chemical, a physico-chemical or a bio-chemical process, whereby each of these processes makes use of the most suitable type of biomass.
A comparison between biomass and other renewable energy suppliers such as photovoltaics, wind power plants or CSP power plants, provides an overview of the best possible mode of application.

Furthermore, a focus is put on wood and the necessary pre-treatment for gasification. In order to ensure an ideal gasification process, some parameters of the quality of wood have to be controlled before its usage. Freshly harvested wood is not suitable for gasification and is therefore dried until a moisture content of 15 to 20 percent is reached. By comparing the advantages and disadvantages of different types of dryers, a selection is made facilitating the choice of the most suitable dryer for gasification.
In order to describe the behaviour of the drying medium (superheated steam) and wood moisture at the inlet and outlet side of the rotary drum dryer, a simplified mathematical model was carried out. An examination of the international market regarding such apparatuses provides an overview of the most important producers. All the information obtained is used to find main parameters affecting size, performance and costs of a rotary drum dryer.

Contents

1. Introduction

The energy policy that has been pursued so far will have to change in order to cover the energy demand of electricity as well as heat or liquid combustibles. The overuse of fossil energy has lead to global warming and consequently to unpleasant weather conditions and unpredictable environmental changes which can have a negative impact on human beings. In order to counter this situation, a global rethinking would have to take place. Thus, it is necessary to use energy sources which do not damage the environment and are also available for everyone.

On average, the surface of the upper earth atmosphere reaches 1353 W/m^2 [1] of short-wave sun rays. Most of this energy (26 percent) is reflected directly and another 19 percent are absorbed by the clouds and the atmosphere.
The surface of the earth reflects another 4 percent which means that in total only 51 percent of the energy reaches the earth's surface. These 51 percent can be harnessed by means of a variety of natural and synthetic processes or photosynthesis by plants which capture sunlight energy and convert it into chemical energy. However, most of the sun energy balances the differences in the atmosphere through:

- evaporation of water
- air movements (wind) which occur because of different temperatures

This has lead to different climate zones entailing a variety of effects on plants and consequently on their growth.

1.1 Solar radiation

By plotting the annual short-wave radiation upon the earth's surface, one can see how affected different regions are. In his book Ben Sorensen published such a world map (cf. figure 1.1). This map looks very similar to Koeppen's climate classification system, which will be introduced in chapter 2.1.

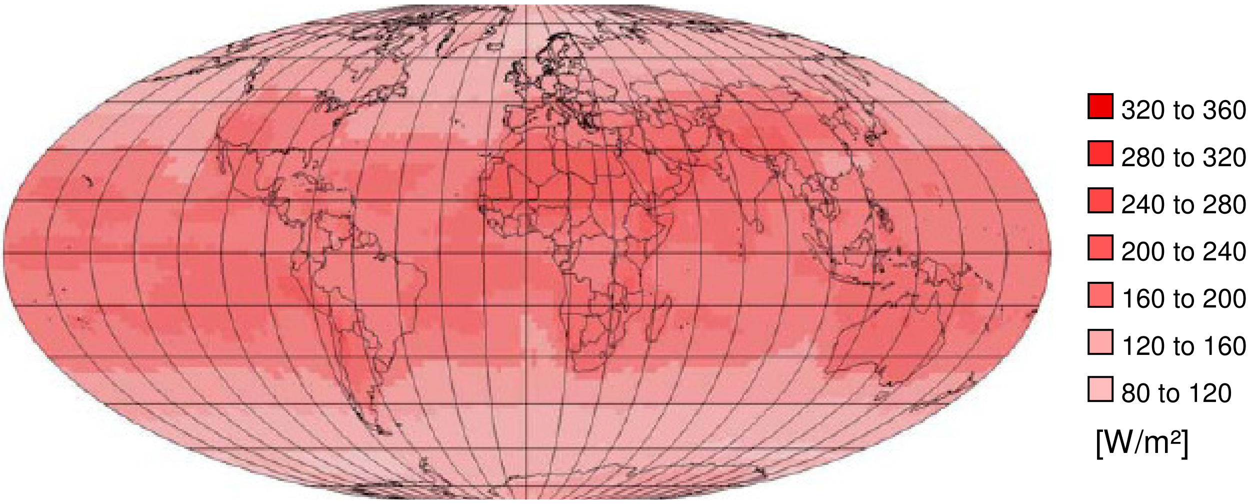


Figure 1.1 Annual solar radiation[1]

In general, the solar radiation is rather balanced, but the sunrays hit the surface under different angles, which in the end results in different climate zones.
Figure 1.2 shows that the quantity of light hitting the surface depends on the position of the sun. The sunrays hit the equator between 23 ° N and 23 ° S latitude, at a direct angle. Radiation that reaches the atmosphere in this area is highly intense. In all other areas, the sunrays hit the surface under a different angle and are therefore less intense. The closer an area is to the poles, the smaller the angle and thus less intense the radiation.

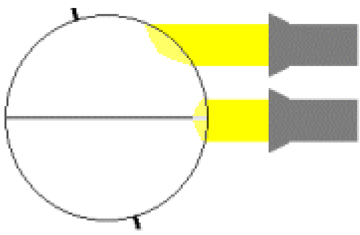


Figure 1.2 Different positions of the sun and the related radiation intensity

In relation, the earth ground plays a decisive role as well. Snow for instance reflects 80 – 85 percent of the radiation, sand 20 – 30 percent, forests 10 – 20 percent and water surface 5 – 80 percent, depending on the irradiation angle.

[1] Sørensen, Third Edition, p.51

1.2 Aim

It is difficult to capture and store sun energy. Plants do so by means of photosynthesis and thereby convert sun energy into a chemical form. In average, plants in tropical regions have higher photosynthesis efficiency and therefore grow faster, leading to a higher yield of biomass per hectare.

How high is the efficiency and are there some factors which are affecting and controlling this process? Is it possible to calculate the highest possible efficiency of photosynthesis? The answer will be discussed in chapter 2.1.1, showing the maximum storage of energy in biomass. The assumption that all sunrays which hit the earth's surface are converted into chemical energy, forms the basis of this evaluation. Current data of some crops will show that there exists a huge gap between the maximum and the actual energy storage.

Another important aspect is a possible biomass conversion in different products and their estimation of costs. Since the price of fossil energy is constantly rising, the chance to bring these new products on the market is high. Improved technology for biomass conversion will ease the achievement of lower prices through increased efficiency and this will consequently lead to more business competition.
Also other renewable technologies adapt further development and constantly obtain higher efficiency and lower production costs.

While the first part of this paper focuses on plants and their application as energy sources, the second part deals with wood chips and their utilisation.

Primarily, it is important to look at biomass characteristics. One of this property is the moisture content in wood, which has to be at a level of 15 - 20 percent in order to enable a gasification process. During the drying process of wood chips, which is necessary before wood gasification, the strong interaction between the wet wood and its surroundings leads to complicated equations which are difficult to describe.

Furthermore, an overview of the dryer classification and the selection of certain types of dryers which are most suitable for gasification, will be given. A simplified mathematical model for the drum dryer provides the opportunity to roughly calculate some dimensions. The calculation and feedback information from companies producing such equipment will help to show which main parameters affect size, performance and costs of a dryer.

2. **Energy in biomass**

2.1 Classification of the possible climate areas

Most world's climate-classification systems used today are based on the one introduced in 1900 by the Russian-German climatologist Wladimir Köppen [2].

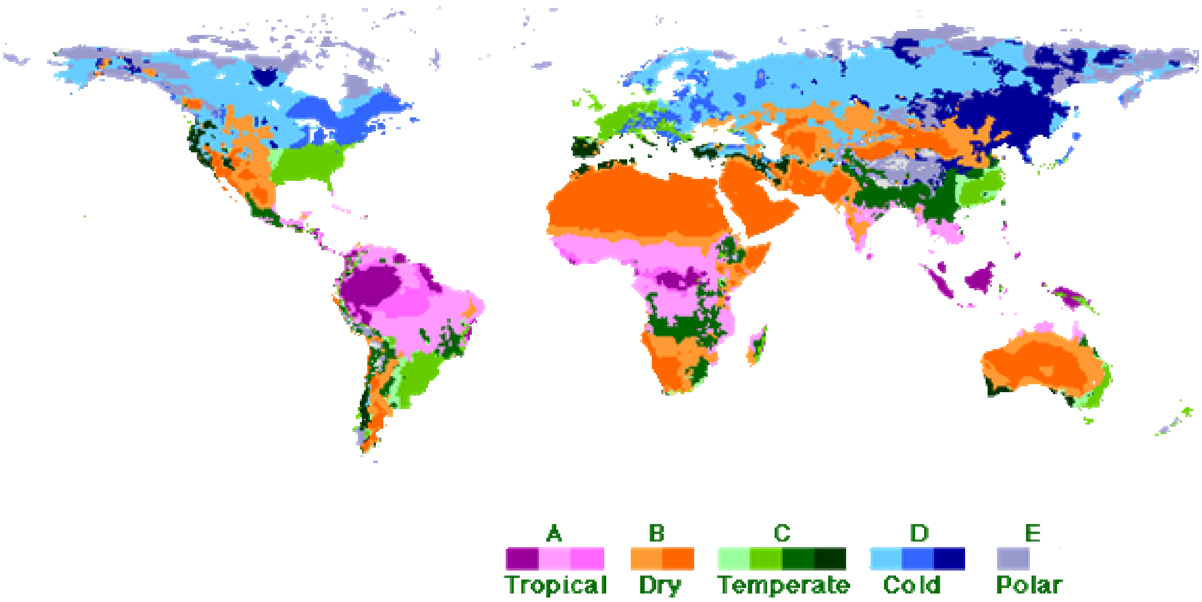


Figure 2.1 Köppen's Climate Classification System [2]

The Köppen system recognizes five major climate types based on annual and monthly averages of temperature and precipitation [2].
Due to the complexity of this system, the model has been reduced to only three climate zones for further application.
Low-latitude climates:

These climates are controlled by equatorial a tropical air masses.

- Tropical moist climates rainforest
- Wet-dry tropical climates savannah
- Dry tropical climate desert biome

[2] Cf. http://geo.bildungszentrum-markdorf.de/fortbildung/pages/grafan3.htm#8

Mid-latitude climates

Climates in this zone are affected by two different air-masses. The tropical air-masses are moving towards the poles and the polar air-masses are moving towards the equator.

- Dry mid-latitude climates steppe
- Mediterranean climate chaparral biome
- Dry mid-latitude climates grasslands biome
- Moist continental climate deciduous forest biome

High-latitude climates

Polar and arctic air masses dominate these regions.

- Boreal forest climate taiga biome
- Tundra climate tundra biome
- Highland climate alpine biome

2.2 Photosynthesis and conversion in energy

The equation for photosynthesis can simply be described as:

$$6\,CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{Sunlight}} \underset{\text{(glucose)}}{C_6H_{12}O_6} + 6O_2 \qquad (2\text{-}1)$$

The energy for photosynthesis ultimately comes from absorbed photons and involves a reducing agent, which is water in the case of plants, releasing oxygen as a waste product. Solar energy is converted into chemical energy [3].

For every CO_2 molecule which is fixed during photosynthesis, nearly 114 kilocalories of energy can be stored in the plant. Considering all processes involved in photosynthesis shows that there are some limitations concerning efficiency [4].

Net efficiency = 0,45 * 0,85 * 0,75 * 0,281 ~ 8 percent (2-2)

At which: Photosynthetically active radiation: ~ 43 – 45 percent of solar radiation

Fraction of incident light absorbed: ~ 80 – 85 percent

Non-respired energy retention: ~ 75 percent

At which 0.281 is the maximum efficiency of white light absorption.

According to field observations, the net efficiency of 8 percent cannot be achieved in practice because of decreasing factors such as poor absorption of sunlight due to its reflection or the need for ideal levels of solar radiation. According [2], [7] the overall photosynthesis lies between 1 and 6 percent. This demonstrates that the actual efficiency that can be achieved is much lower than the theoretical one.

The main factors which are affecting photosynthesis are [3]:

- Light irradiance and wavelength
- Carbon dioxide concentration
- Temperature
- Water availability
- Availability of inorganic ions

Being under the influence of the above named factors and under favourable conditions, plants can reach the following maximum of productivity

for short time	C4-plant, Tropic	400 kg ha^{-1} day^{-1}
	C3-plant, Europe	200 kg ha^{-1} day^{-1}
annual average	C4-plant, Tropic	80 t $ha^{-1}yr^{-1}$
	C3-plant, Europe	20 t $ha^{-1}yr^{-1}$

Table 2.1: The maximum productivity of agro plants under favourable conditions [4]

The differences between C4 and C3 plants is that the C4 plants use an enzyme called PEP (Carboxylase) which is responsible for producing the 4 carbon molecule oxalloacetic acid. The latter do not contain this enzyme and their primary carboxylation reaction produces the three carbon sugar 3-phosphoglycerate. C4 plants reverse the reaction mentioned above, when the oxygen level in the leaf rises and therefore prevents photorespiration. Consequently, C4 plants can produce more sugar than C3 plants under favourable conditions such as strong light and high

[3] Cf. Rowland Martin; 1992; p.155

[4] Cf. http://de.wikipedia.org/wiki/Photosynthese; translate into English

temperatures. Some C4 plants, like for instance sugarcane, are already used for biomass production. [3]
The differences between the individual climate zones are shown in table 2.2 which contains rough information on the annual average amount of photosynthesis net-production:

Tropical forest	9,9 t $ha^{-1}yr^{-1}$
Hardwood forest	5,8 t $ha^{-1}yr^{-1}$
Coniferous forests	3,6 t $ha^{-1}yr^{-1}$
Savannah	4,1 t $ha^{-1}yr^{-1}$
Grassland (Mid-latitude Climates)	2,7 t $ha^{-1}yr^{-1}$
Tundra	0,6 t $ha^{-1}yr^{-1}$

Table 2.2: The annual average amount of photosynthesis net-production [4]

2.2.1 Maximum storage of energy in biomass

In order to calculate the maximum storage of energy in biomass, crucial information about the basic components of biomass is necessary (cf. tables 2.3 and 2.4). When biomass is separated into its individual parts which are lignin, cellulose and hemi-cellulose, one can notice that cellulose takes up the biggest part. The High Heating Value HHV of these (cf. table 2.4) is necessary for calculation.

Biomass	Lignin (%)	Cellulose (%)	Hemi-cellulose (%)
Softwood	27 – 30	35 – 40	25 – 30
Hardwood	20 – 25	45 – 50	20 – 25
Wheat straw	15 – 20	33 – 40	20 – 25
Switchgrass	5 – 20	30 – 50	10 – 40
Bagasse	18	41	24
Rice straw	6	35	35

Table 2.3: Biomass rates of the main components [7]

Component	HHV (dry) [MJ/kg]
polysaccharides	17,5
cellulose	17,5
lignin	25,1

Table 2.4: High Heating Value of some biomass components

The following equation shows an estimation of the maximum output of crop fields.

$$Yield = \frac{Average\_insolation * Solar\_energy\_capture\_efficiency}{HHV} * 3.1536 * 10^7 \frac{\sec}{yr} \quad (2\text{-}3)$$

Yield …	[t/m²yr]
Average insolation …	[MW/m²]
HHV …	[MJ/t]

The High Heating Value in this equation is that of cellulose and is 17,5 MJ/kg. The value at the end of formula (2-3) which is $3{,}1536*10^7$ represents the number of seconds in one year. Many international organisations or public authorities provide the actual values of the average insolation from around the world.

In order to calculate the highest achievable crop yield, the solar energy capture efficiency should be at its maximum. As it was shown in chapter 2.2, the maximum is reached at 8 percent. A list of selected places is presented in table 2.5, and contains the annual average insolation, converse from kWh/m²day to W/m², and result of crop yield with the units [t ha^{-1} yr^{-1}].

Country	State/City	Year Avg [kWh/m²day]	Average insolation [W/m²]	Yield [t ha^{-1} yr^{-1}]
F	Paris	3,34	139,2	201
IT	Milan	3,33	138,8	200
N	Oslo	2,27	94,6	136
UK	Edinburgh	2,26	94,2	136
EG	Cairo	5,68	236,7	341
TN	Tunis	4,7	195,8	282
AR	Buenos Aires	4,39	182,9	264
CAN	Toronto	3,44	143,3	207
AU	Perth	5,16	215	310
CN	Shanghai	4,01	167,1	241
IN	New Delhi	5,1	212,5	306
KR	Seoul	4,16	173,3	250
TR	Ankara	4,17	173,8	250
NZ	Auckland	4,34	180,8	261
MY	Kuala Lumpur	4,7	195,8	282

Table 2.5: Current values of the average insolation at selected places[5]

[5] Cf. www.apricus.com/html/solar_collector_insolation.htm, Average Insolation (10 year average), net efficiency 8 percent and HHV =17,5 MJ/kg

The current values of the average insolation in some states of the USA are available in appendix 1. The average insolation of the continental US lies between 125 and 375 [W/m²] [6], and after the use of the equation (2-3) the possible yield [t ha^{-1} yr^{-1}] should amount between 180 and 540 t dry biomass/ha/yr.

For further consideration, Europe will be divided into four areas and the classification and accurate composition are shown in appendix 2. In order to get more significant answers to biomass productivity, it is useful to put together places with similar weather conditions. The reason why only Europe is divided into areas and the USA are not, might be that Europe is of more interest.

The areas Europe is divided into:

Middle Europe, North-mainland Europe, North-island Europe and South Europe. The average insolation of three cities in each area is taken for calculation (cf. appendix 2). North island and north mainland show very similar values for their average insolation which is why in the course of this paper only the north European area will be considered.

A comparison between some types of energy plants in different areas in the USA, Europe and Brazil shows table 2.6.

The differences in the amounts of yield between plants of the same area varies from a couple of tons to negligibly small amounts.

Biomass	Country	HVV (MJ/kg)	Average insolation [W/m²]	Yield [t ha-1 yr-1]
Switchgrass	USA	17,4	184	267
Soybeans	USA	21	184	221
Sugarcane bagasse	Brazil	17,33	209,6	305
Switchgrass	Europe/north	18,5	106	145
Switchgrass	Europe/middle	18,5	134,3	183
Willow	Europe/north	20	106	134
Poplar	Europe/north	19,38	106	138
Miscanthus	Europe/north	17,4	106	154
Miscanthus	Europe/middle	17,4	134,3	195
Miscanthus	Europe/south	17,4	200	290
Reed canary grass	Europe/north	18,37	106	146

Table 2.6: The maximum theoretical output of different plants [7]

[6] Cf. http://www.solarpowerfor.us/solar-power.html
[7] Note: HHV values from table 4.1, net efficiency 8 percent

Sugarcane bagasse, is known as a fast growing plant yielding excellent harvests. With the theoretical amount of 305 t/ha/yr, this plant achieves the highest possible crop yield which is also true in practice.

2.2.2 Actual storage of energy in biomass

There are several aspects which affect photosynthesis and thus the crop yield which is smaller than the one calculated in section 2.2.1. The number of disturbing factors is enormous and some of these factors are listed at the beginning of chapter 2.2. Scientists are working on the production of faster growing plants with higher yield rates [28]. A certain improvement has already been achieved, yet there is still more that needs to be done regarding some plants and their future application.
As table 2.7 shows, the efficiency in capturing energy is evidently smaller than the theoretical maximum of 8 percent. The list shows common types of plants growing at good locations.
In comparison, the high yield of two plants attracts attention. Sugarcane, which is widely used as agricultural product, delivers the highest yield among plants.
The second most efficient plant is the green algae from Thailand which achieves 4,9 percent and compared to other plants demonstrates perfect energy storage. However, their utilisation for plant cultivation has been proved difficult.

Location	Biomass community	Annual yield dry matter (t/ha/yr)	Average insolation	Solar energy capture efficiency (%)
Alabama	Johnsongrass	5,9	186	0,19
Texas	Switchgrass	8-20	212	0,22-0,56
Alabama	Switchgrass	8,2	186	0,26
Sweden	Enthrophic lake angiosperm	7,2	106	0,38
Texas	Sweet sorghum	22,2-40	239	0,55-0,99
Minnesota	Maize	24	169	0,79
Israel	Maize	34,1	239	1,79
Holland	Maize, rye, two harvests	37	106	1,94
England	Coniferous forest 0-21 years	34,1	106	1,79
Congo	Tree plantation	36,1	212	0,95
West Indies	Tropical forest, mixed ages	59	212	1,55

Location	Biomass community	Annual yield dry matter (t/ha/yr)	Average insolation	Solar energy capture efficiency (%)
Hawaii	Sugarcane	74,9	186	2,24
Java	Sugarcane	86,8	186	2,59
Puerto Rico	Napier grass	106	212	2,78
Thailand	Green algae	164	186	4,9
Minnesota	Willow and hybrid poplar	8,0-11	159	0,30-0,41
New South Wales	Rice	35	186	1,04

Table 2.7: Biomass productivity and solar-energy capture efficiency [8]

A high average insolation is not automatically connected with a better yield effect which would mean a higher solar-energy capture efficiency. In England, coniferous forests achieve a higher efficiency than tropical forests in the West Indies or tree plantations in Congo. The proper adaptation of plants to the area and the surrounding environment are even more relevant.

Experience with the cultivation of energy crops are rather limited and a progress to higher yields is supposable. In order to increase the efficiency for solar energy capture, the manipulation of photosynthesis will be required.

Considering the harvest results for agricultural products like wheat, barley, corn or rice, which are summarised in table 2.8, it is obvious that long-time experience results in increasing yields, yet the theoretical 8 percent cannot be reached. Furthermore, an unsatisfactory policy as well as bad environmental conditions have caused a decrease in efficiency, which can be seen by comparing the EU-25 rice yield to other regions.
The changes in yields of agricultural products over the last 30 years will be discussed in chapter 2.3.

The table below shows the yields of different agricultural products in several countries/regions between 2003 and 2004. The increase in productivity did not result from improvements but is rather due to annual fluctuations.

[8] Cf. Klass; 2004; p. 195

	Wheat Yield and Production		Barley Yield and Production		Corn Yield and Production		Rice Yield and Production	
	Yield [metric tons/ha]		Yield [metric tons/ha]		Yield [metric tons/ha]		Yield [metric tons/ha]	
Country/Region	2003	2004	2003	2004	2003	2004	2003	2004
North & South America								
United States	2,97	2,9	3,17	3,74	8,93	10,07	7,48	7,78
Canada	2,25	2,62	2,77	3,26	7,8	8,25	-	-
Europe								
EU-25	4,85	5,88	4,08	4,73	6,61	8,36	2,66	2,71
Asia & Oceania								
Australia	2	1,64	2,32	1,67	-	-	8,36	6,73
China	3,93	4,25	3,51	3,63	4,81	5,12	6,06	6,31
Africa								
South Africa	2,06	2,02	-	-	2,94	3,64	-	-
Egypt	6,26	6,07	-	-	8,54	8,5	9,84	10

Table 2.8: Yield and production of agricultural products in the years 2003 and 2004 [9]

Another good example showing that insolation is not the only crucial factor assuring a high yield are the following data, quoting ten countries with the highest cereal yield and ten countries with the lowest [14]. Among the top ten countries denoting the highest yield are those having an average insolation of 106 W/m, whereas countries having a very high average insolation are among the top ten countries denoting the lowest yields.

The choice for the best application of crop (cf. table 2.7) depends on several factors which vary from area to area. Apart from the annual output of biomass, other choices could be of interest such as the starting of harvesting and cycle's time. Table 2.11 specifies biomass, the annual dry output and the time for the first harvesting and cycle time. Grass crop can be harvested annually, whereas Switchgrass up to three times per year. For Short Rotation Coppice SRC (wood crop), the harvesting cycle is around three years and this has lead to a plantation design describing [27] the arrangement of the annual harvest.

[9] Cf. http://www.fas.usda.gov/wap/circular/2005/05-12/toc.html

Biomass	output dry t/ha/yr	Time
Miscanthus *	13 - 30	from 3rd year for the next 10 years
Reed canary grass **	8 - 11,5	annual
Miscanthus **	15 - 25	from 3rd year annual
SRC Willow *	10 - 15	cycle 3-5 year
Poplar *	10 – 15	cycle 3-5 year
Switchgrass *	~ 8	up to 3 cuts per year

Table 2.9: Energy crop output and harvesting cycles [10]

2.3 Comparison of maximum and actual storage of energy in biomass

In general, the characteristics of the ideal energy crop can be described as follows:

- High yield (maximum production of dry matter per hectare)
- Low energy input for production
- Low cost
- Composition with the least contaminants
- Low nutrient requirements

It is difficult to provide a summary of the data on the productivity of different energy plants because of the differences in techniques used and ways of representing the results. Field tests that are conducted in order to get data of productivity and the plant behaviour often take place under controlled and optimal conditions. The problems with this information is that it does not reflect the behaviour under normal condition of particular plants. Some statistical information for whole regions does not convey the exact conditions of growth and furthermore, the productivity of a plant can depend on the early application of the land [1].

[10] Sources: * [7], **[12]

The information collected in chapter 2.2.1 and 2.2.2 shows that the net efficiency is much smaller than the theoretical maximum. It ranges from 0,19 percent for Johnsongrass in Alabama to 4,9 percent for Green algae in Thailand (cf. table 2.7). Most of the plants usually do not achieve the barrier of 2 percent. Green algae in Thailand show the best results but are currently not utilised as energy supplier. Sugarcane, which is widely used as alternative fuel in urbane Brazil, is commonly used as it reaches a peak in solar-energy capture efficiency (cf. table 2.7). There are certain defined factors that have an effect on the high productivity of some plants, but these can hardly be controlled by mankind.

Factors affecting biomass yield:

- Insolation
- Rainfall
- Temperature
- CO_2
- Land availability
- Nutritional value of soil

The first three factors specify the climate zone. How these factors positively affect the productivity of a plant will be shown in table 2.10. This table shows the average yield of Eucalyptus plantations of five different bio-climate regions in the north of Brazil. A strong deviance can be noticed in the amount of rainfall and the resulting water deficit. The differences in the projected average yield are huge and range between the best and worst result amounts to 17,9 dry t/ha/yr.

	Bio climate region				
Bio climate characteristics	1	2	3	4	5
Rainfall [m/yr]	1,5 - 2,3	1,0 - 1,7	0,7 - 1,3	0,5 - 1,0	0,25 - 0,6
Water deficit [m/yr]	0 - 0,1	0,05 - 0,3	0,2 - 0,6	0,5 - 1,0	0,8 - 1,3
Average temperature [°C]	22 - 28	24 - 28	24 - 28	26 - 28	24 - 28
Elevation [m]	0 - 700	<900 - 1000	<700 - 1000	<700	<600
Projected average yield [dry t/ha/yr]	20,7	15,5	13,2	7,1	2,8

Table 2.10: Estimated average yield of Eucalyptus grown on plantations in different bioclimatic regions of northeast Brazil. [11]

[11] Cf. Larson; 1993; p. 580

On the other hand not only the bio climate can have an influence on the yield but also can improvements in harvesting techniques and cultivation lead to increased yield. The gap in the amounts between countries with the highest cereal yield and those with the lowest is more than twenty fold [14]. However, through improvements in agricultural techniques, the yield has been increased every year how figure 2.1 shows.
The manipulation of photosynthesis to increase the initial capture of light energy is more promising. In the last years this technique has been successfully applied and a significant increase has been achieved. Arthur J. Ragauskas mentions that "(…) *in a 3-year field trial of transgenic poplar (P. tremula x P. alba) over expressing a glutamine synthase gene, tree height increased to 141% that of control plants by the third year.*" [12]

The application of such techniques for energy crops has not been a problem for farmers up to now, yet there is more and more a tendency towards using genetically modified cereals in order to gain liquid or solid fuel. Cereals like barley, wheat, oat and rye can be used to produce ethanol and the straw can be used as a solid biofuel. The above mentioned improvements in the agricultural sector have lead to changes of the average crop yield. Figure 2.1 presents the US average for the last 35 years showing a linear regression trend line. It shows that the average corn yield annually increased annually by 3,5 percent [30].

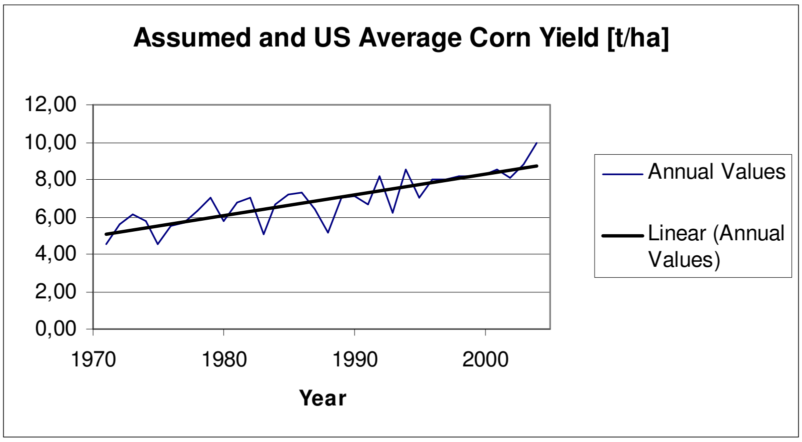


Figure 2.2: Changes and possible progression of average corn yield in the US [13]

[12] Ragauskas; 2006; p.485
[13] Cf. Farrell et al.; Version 1.1.1 Updated July 13, 2006; p.17

Also a higher stocking percent on the field does not always lead to an increased output. The Danish biomass information network „Centre for Biomass Technology" researched if a higher number of plants (tree) per hectare would automatically lead to a higher yield. As expected the results show that at the beginning of this procedure an increase was registered. The method to increase the number of plants will only be of interest until the point is reached at which the output rises just minimally (cf. Figure 2.3). Figure 2.3 shows that, if the number of trees is raised also the volume of wood chips per hectare will increase, but the progression is dying out after it has reached around 7000 – 8000 plants per hectare.

Figure 2.3: Wood chips production in cubic meter – number of plants per hectare [14]

There are many ways how to increase yields but for future agricultural and energy policy also the following problem must be considered.

"*In most regions of Europe, there will be a choice of bioenergy crops under future climate, but all models and scenarios suggest that most of southern Europe will be particularly vulnerable to climate change.*" [15]

This factor will have an enormous influence on the future agricultural policy in the EU. In some areas of Southern Europe the consequence for overexploitation of natural resources as water through irrigation is already noticeable. "*There may be some limited opportunities for other Mediterranean-type crops to be grown here, for example, sorghum and prickly pear, but overall the choice of potential biofuel crops in this area will be severely reduced.*" [15]

[14] Cf. Serup et al.; Second Revised Edition 2002; p. 11
[15] Tuck, Glendining et al.; 2006; p.196

Some solid bio fuel crops will progressively decline in Mediterranean regions, mainly in Spain [24]. Future demands for bio fuels assign a new task for scientists. Besides an increase of yield, scientists have to make efforts such as breeding for temperature/drought tolerance or alternative management-strategies to counter the challenges presented by climate changes.

Graham/Lichtenberg et al. presented an estimation of the potential production of biomass in the United States under a range of assumptions. It shows the potential progress for crop earnings of biomass research programs: 2000 - yields attainable with current technology, 2005 - yields with improved management, clonal and varietal selection, and 2020 - yields that could be achieved with a sustained multi-regional genetic improvement program [16].
These studies suppose that for some crops an increase of more than 100 percent during the next 20 years will be possible.

Anther important aspect, not for the efficiency but more for future plans is the structure of the agricultural land which varies from continent to continent. According to some reports, the average farm size in the EU-25 is 15,8 hectare [10] and an US average is 178,5 hectare [11]. With the available data about the farm size an ideal arrangement of an energy farm can be done and thus cost reduction and best operation in terms of biomass production are possible. A design example of Short Rotation Coppice SRC plantation describes, where a 20 hectare plantation is separated in three areas which contain three age classes of SRC. The proposal for this design should maximise production and harvesting efficiency, as well as potential environmental benefits [27].

3. Production costs and gains of biomass

A multitude of different biomass products is available on the market as well as by-products like nut shells, olive stones, straw or energy crop that has especially been cultivated for that purpose. Its utilisation is rather limited and therefore both cultivation and harvesting techniques are still rather inefficient and costly.

The supply of biomass for conversion facilities has lead to logistic problems and must be well thought through, because the distance from the resource area to the conversion facility can be rather long. In order to maintain the demand of, it might be necessary to transport it to another country or even another continent. If long distances are to be covered or where international transports are necessary, additional costs and a higher energy consumption are to be faced compared to using locally available biomass.
In chapter 2.3, the discussed characteristics of an ideal energy crop are have a great influence on the costs of biomass and are determining factors for a following economic success.
On the one hand, the price for biomass should be as small as possible for the conversion (dissipate) factory, on the other hand sufficient in order to cover the farmers' expenses for cultivation. Offering an incentive for farmers who cultivate energy crops the European Union provides subsidization. At this point it is to say that every EU country has its own system of subsidization and it is difficult to encounter an overview of all of them.

3.1 Current prices of some biomass products

Given data of biomass prices often do not provide any information on what is included and how they are subdivided. Some documents do not deal with the climate zones where the cultivation took place. In such cases it is important to know more about the circumstances.
As shown in tables 2.9 and [14], Egypt achieves a very high cereal yield due to great energy input, especially of irrigation. Also in southern EU countries crop areas are only maintained by means of high irrigation. This has not only lead to increased

prices but also to problems such as sinking ground water level and consequently the drying-up of lakes or rivers.

A difference in prices might also result from different average farm sizes and according to this the need for machines and required manpower and the purchase price. An average US farm with 178,5 hectare [11] has more funds which can be invested in modern machinery and improved technology, compared to an average EU-25 farm size of 15,8 hectare [10].
On this account, Hamelinck et al. suggest producing energy crops in for instance the Ukraine, where land costs and employees' income are lower and additionally farms are much bigger.

Biomass residues from forestry or industry are cheaper and often closer and therefore easier available for the end user, whereas the recycling of these sources is already common practice [31].

Costs for crops are strongly varying because of different needs, for instance in harvesting or machinery. The following enumeration provides an overview of important factors which have an influence on the price. It is difficult to list them exactly according to their importance.

- Seed
- Irrigation
- Fertilizer
- Herbicide
- Machinery fuel
- Repairs
- Depreciation
- Insurance
- Taxes
- Workers' payments
- Land rental

A summary of the harvesting cost for dominant crops and straw will be given in table 3.1. These data provide an overview of the situation in several US regions with good surrounding conditions [17].

Commodity	Harvest cost [$/t]
Corn	12,73
Winter wheat, continuous	15,66 - 20,97
Sorghum	16,6 - 16,73
Spring wheat, continuous	19,42
Barley	17,34
Oats	18,66
Rice	20,32
Corn stover	41,9
Sorghum stover	42,51
Wheat straw	21,21
Barley straw	32,09
Oat straw	34,25
Sugarcane bagasse	6,31
Rice straw	25,1

Table 3.1: Harvesting cost for dominant crops in US [17]

This information was compiled in 2003 and as shown in table 2.9, the average yield is increasing from year to year.

Costs for residues vary between ~6 $/t [16] for sugarcane bagasse to ~43 $/t for sorghum stover. The price for sugarcane bagasse is very low because costs for harvesting, transport and fertilizer are associated with the primary sugar crop [17]. Straw might be of special interest to the industry as it is a cheap energy supplier. In order to supplement their income, farmers might consider selling straw to the biomass conversion plant.

The biggest disadvantages of this type of biomass for energy use are the low density and aggressive combustion gases. Chapter 6 will provide information about the density of different biomass products (cf. table 6.3) including a detailed description how to handle them.

[16] Assuming that the 1 Euro = 1,15 US$ (2003)

Data for European producer prices, especially for quantities, producer prices, selling prices or purchase prices of agriculture products, are available on the Internet.

CEREALS (including seeds)	94,48	a)
Wheat and spelt	97,37	b)
Durum wheat	132,36	c)
Barley	93,69	d)
Rice	138,57	e)
Rape and turnip rape seed	151,55	f)
Sunflower	161,82	g)
Soya	185,81	h)
Sugar beet	32,79	i)

Table 3.2: Unit values at producer prices in Europe [Euro/t] (2004); abstract [17]

The table above shows the average prices for some agricultural products. The composition of these values is affected by different European countries. The exact listing of these countries will be given below.
Whilst values in table 3.1 only represent the harvesting costs, table 3.2 contains the producer prices which include all expenditures incurred by farmers.

A typical biomass source is wood which is common for domestic use but arouses strong interest to be utilized in large conversion plants. A summary of wood fuel prices for Europe in 2002/2003 will be given in the following table which provides an overview of ten European countries with the classification in wood chips, pallets, briquettes, logs and straw. Furthermore, quotations for domestic and large scale consumers are also given. The prices are highly varying, also the manner how they are declared differs to some extent. Finland for instance often uses the calculation €/MWh, while other countries prefer €/kg.

As already mentioned before, the prices given are from 2002/03, thus before the last oil crisis in the year 2006. Increasing prices for gas and oil have lead to an increased demand for biomass products, which again resulted in rising costs.

[17] a) CZE, DEN, GER, EST, IRL, LAT, LTU, LUX, HUN, AUT, POR, FIN, SWE, BUL
b) CZE, DEN, GER, EST, IRL, ITA, LAT, LTU, LUX, HUN, AUT, POL, POR, SLK, FIN, SWE, BUL
c) GER, FRA, ITA, HUN, AUT, POR, BUL, ROM
d) CZE, DEN, GER, EST, FRA, IRL, ITA, LAT, LTU, LUX, HUN, AUT, POL, POR, SLK, FIN, SWE, BUL, ROM
e) GER, FRA, ITA, HUN, POR, BUL, ROM
f) CZE, DEN, GER, EST, FRA, ITA, LAT, LTU, LUX, HUN, AUT, POL, POR, SLK, FIN, SWE, BUL, ROM
g) CZE, GER, FRA, ITA, HUN, AUT, POR, SLK, BUL, ROM
h) CZE, FRA, ITA, HUN, AUT, SLK, BUL, ROM
i) CZE, DEN, GER, EST, FRA, IRA, ITA, LAT, LTU, HUN, AUT, POL, POR, SLK, FIN, SWE, BUL, ROM

Fuel / Country	Wood chips-for large scale user	Wood pellets - for large scale user	Wood chips - for domestic user	Wood pellets - for domestic user	Wood briquettes	other pellets (identify)	Wood logs - for domestic user	Straw, large scale user
Austria	0,066 €/kg	-	0,17 €/kg		0,20 €/kg	-	0,1 €/kg	
Belgium	47 €/t (forest) 32 €/t (sawmill)	155 €/t	-	260 €/t (in 15kg bag)	-	-	32 €/t (wet) 67 €/t (dry)	-
Denmark	45 €/ton @40%H2O	133 €/ton	200 €/ton			not used	160 €/ton	55 €/ton @15H2O
Finland	9,8€/MWh	19,3 €/MWh	-	26,1 €/MWh	-	-	46,3 €/stacked m³ (brich) 35,9 €/stacked m³ (mixed)	-
France	36,6 €/t	121,9 €/t	51,8 €/t	219 €/t	-	-	38,1 €/m³	32 €/t
Germany	10 €/m³	140 €/t	-	170 €/t	-	-	-	-
Italy	0,045-0,064 €/kg	0,091-0,182 €/kg	-	0,2-0,23 €/kg	-	-	0,091-0,182 €/kg	
Spain	0,024 €/kg	-	-	-	-	-	0,09 €/kg	
Sweden	-	83,3 €/t	-	164,8 €/t	-	-	-	-
United Kingdom	22 – 45 €/t	-	-	135 – 180 €/t	-	-	75 €/t	-

Table 3.3: Wood fuel prices in Europe in 2002/2003; sources [16]

One reason for last year's strong demand for biomass, especially for wood, is that many domestic users changed their old heating systems to systems operating with wood chips or pellets. A second reason is the changeover in the European energy sector. The stronger demand for renewable generated electricity and heat has lead to the construction and application of new systems for biomass power plants, mostly using wood as a fuel source. This involved a rapid increase in the prices for wood chips and pellets. As shown in figure 3.1, the price for biomass fuel for central heating was constant in the past.

Another confirmation of the wood price stability in the last years is given by the report from Danske Fjernvarmeværkers Forening (an association of Danish district heating plants) which has, for many years, kept statistics on how much district heating plants pay for the various fuels. It shows that prices for fossil fuels vary considerably while prices for bio fuels have remained constant. An exception are the prices for wood pellets which have slightly increased since 2002 [20].

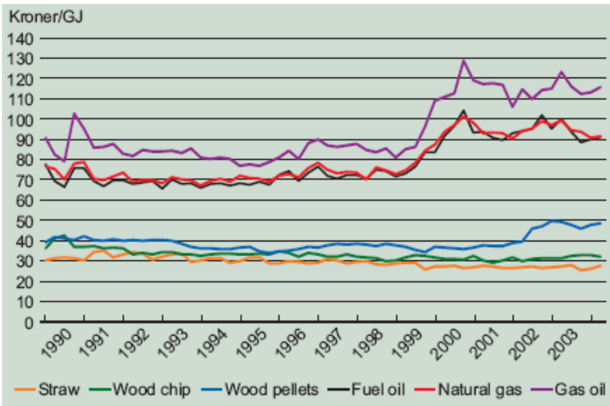


Figure 3.1: Fuel prices for central heating plants from 1990 to 2004. [18]

In the last years the price differences between fossil fuels and bio-fuels have increased continuously and it seems that this trend will continue. In the future the demand for fossil fuels will be stronger than for bio-fuels. Furthermore, there are many biomass sources that have not yet been fully exploited.

3.2 Possible gains

The applied utilization of energy crops or in general bio-fuels in power plants depends on:

[18] FIB Bioenergy research; Third issue; August 2004; p. 3

- Price: straw from local farmers
  wood - chips from local forests and/or import, international market
  price NW Europe / Baltic region
  wood – pellets international market price NW Europe / Baltic region
- Quality: low in chlorine and potassium
- Security of supply: harvest, storage and logistics

Both storage and logistic problems are based on low bulk density (cf. table 6.3)

Another aspect which influences utilization and costs are transport distances. Most of the conversion plants are limited in terms of size because of storage and logistic problems which occur when biomass is used as fuel. It is important to have a nearby bio-fuel market. According to Carlo N. Hamelinck et al.”*Truck transport is generally applied for relatively short distances (<100 km), when flexibility is required because multiple (small) production sites have to be accessed, or when train and ship infrastructure is absent.*” and “*Train transport is applied for the longer overland distances (>100 km).*” [19]

High costs not only affect the profitability of power plants but also farmers who have to meet their demands. The Danske Fjernvarmeværkers Forening for example proposed to use heavier straw bales. This could entail lower storage costs as well as a reduction of the conversion costs [20]. In figure 3.2 it is shown how transport costs depend on the distance of transportation and the weight of straw bales.

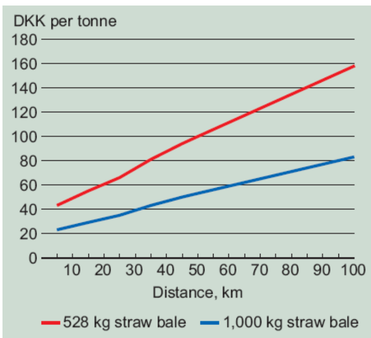


Figure 3.2: Transport costs as a function of distance and weight of straw bales.[20]

[19] Hamelinck et al; 2005; pp.123-124
[20] FIB Bioenergy research; Third issue; August 2004; p.7

Conventional machines reach a maximum of 600 kg straw bales (red line). In order to achieve the aim of straw bales with 1000 kg (blue line), new machines have to be developed or the old ones modified.

By using the information on the selling prices for crops, straw, wood chips and their actual yield being achievable, it is possible to calculate farm incomes with different cultivation plants. These incomes from food production farms and energy crop productions are used to compare the profitability of the corresponding plant. The following comparison will show if a change to alternative energy crop cultivation pays off.

Country	Type		Yield (t/ha)			Price (€/t)			Total
			Seed	Straw	Chips	Seed	Straw	Chips	
Germany	Harvest seed	Soft Wheat	6,49	3,5		108,0	43		851,1
		Barley	5,8	3		93,2	45		675,8
	Harvest energy crop	Miscanthus			20			83 [21]	1660
		Soft Wheat	7,8	5		119,3	43		1145,2
England	Harvest seed	Coniferous forest 0-21 years			34,1			34	1159,4
	Harvest energy crop	SRC willow			12			40	480,0
		Wheat	5,55	3		109,6	43		737,1
Sweden	Harvest seed	Potatoes	26,52			147,2			3904,0
		Sugar beet	57,3			46,1			2643,3
	Harvest energy crop	Miscanthus			20			83	1660
		SRC willow			12			66	792,0
Austria	Harvest seed	Sugar beet	57,61			49,1			2828,9
		Wheat	7,08	4,5		105,5	43		940,2
	Harvest energy crop	SRC willow			12			45	540,0

Table 3.5: Possible gains through cultivation of energy crop or food crop.

3.3 Comparison

Epplin shared the costs for biomass as follows "(…) *14 % for establishment, 22% for land, 32% for annual stand maintenance and harvesting, and 32 for loading and transportation."*[22] and Hamelinck et al. states that "(…) *the crop's costs account for 25–40% of the delivered costs.*" [23]

[21] Source : http://www.agriforenergy.com/Downloads/Miscanthus_Fr%C3%BChwirth.pdf
[22] Francis M. Epplin; Biomass and Bioenergy Vol. 11, No 6; p.459
[23] C.N. Hamelinck et al.; Biomass and Bioenergy; 29 (2005); p.114

Table 3.5 shows that in some cases a change from traditional crop to energy crop is possible in terms of similar income. Additionally, such energy crop farms are designed for long-time use, up to twenty years. Long term contracts with power or conversion plants ensure a regular income for farmers.

It is difficult to get price information on some energy crops, because in many cases the fields are rather considered to be study objects.
Very often, the selling price, especially for straw, is oriented locally and can strongly vary within some kilometres, which makes a comparison very difficult. In order to avoid such problems biomass has to become more comfortable in terms of transportation. Straw for instance is only locally traded but this habit can easily change if the use of straw pellets will become more widespread.

Machines for harvesting are not yet fully developed, they are mostly adapted from the traditional agricultural sector and are only constrictively suitable for these tasks.

Another aspect which should be considered is that energy crops are facing strong competition from traditional crops for high-quality land. Some types of energy crops like sorghum implicate problems with damaging potential on the environment.
In contrast, Switchgrass is less damaging. It is expensive but its yield does not depend too much on the land quality and is therefore suitable for cultivation on lands with lower value [9].

In order to ensure delivery quantity for bigger biomass power or conversion plants, both the local and the international market must be involved. On the international market biomass can be delivered from Europe for 90 and 70 €/t (dry) when shipped as pellets. It is cheaper to purchase biomass from South America as the production costs are much lower there. Despite the long shipping distance, biomass can be bought for 40 €/t (dry). In order to keep down the prices for biomass, the distance from the production facility to the place of selling has to be short and a high biomass yield per hectare is necessary [31].

4. Biomass application

4.1 Conversion possibilities and the products

There exist many databases from which information about the composition of biomass can be received. An important one and therefore noteworthy is the Phyllis database which provides information on almost all biomass types.
An overview of some types of biomass will be given in table 4.1 and 6.1 including information on ash, moisture, volatile compounds and heat value. The types listed below are the most common ones and cover many type occurrences in different climate zones.

Biomass	Ash (wt%)	HVV [MJ/kg] (dry basis)
Red alder **	0,41	19,3
Black locust **	1,05	19,71
Poplar *	1,53	19,38
Dougles fir **	0,1	20,37
Casuarina **	1,59	19,44
Eucalyptus grandis **	0,49	19,35
Leucaena **	1,51	19,07
Sugarcane bagasse **	9,91	17,33
Wheat straw ***	5,9	18,75
Barley straw ***	5,9	18,75
Cereal straw *	4,3	17,3
Sunflower ***	3,5	25,95
Rice straw ***	19,1	15,95
Rape ***	5,5	21,6
Fir *	0,8	21
Danish pine *	1,6	21,2
Willow *	1,6	20
Miscanthus *	2,8	18,5
Switchgrass *	4,5	17,4
Rape seed ***	2,86	19,33
Reed canary grass ***	8,85	18,37

Table 4.1: Biomass characteristics [24]

[24] Sources: * [5]
** [6]
***[http://www.ecn.nl/phyllis/]

As it can be seen in the table above, the ash concentration of straw, grasses and sugarcane bagasse is high compared to most wood species. Furthermore, straw has a low ash melting point and is therefore difficult to handle during the burning process. Melted and sticky ash causes problems for machinery, reduces the efficiency of such plants and produces additional costs for cleaning. Additives help to reduce negative properties.

Harvested biomass has to be prepared through typical physical processes:

- particle size reduction
- separation into two or more components
- drying
- fabrication: pellets, briquettes for further usage

A general overview of possibilities to provide heat and/or power as well as fuels from biomass will be given in the following figure.

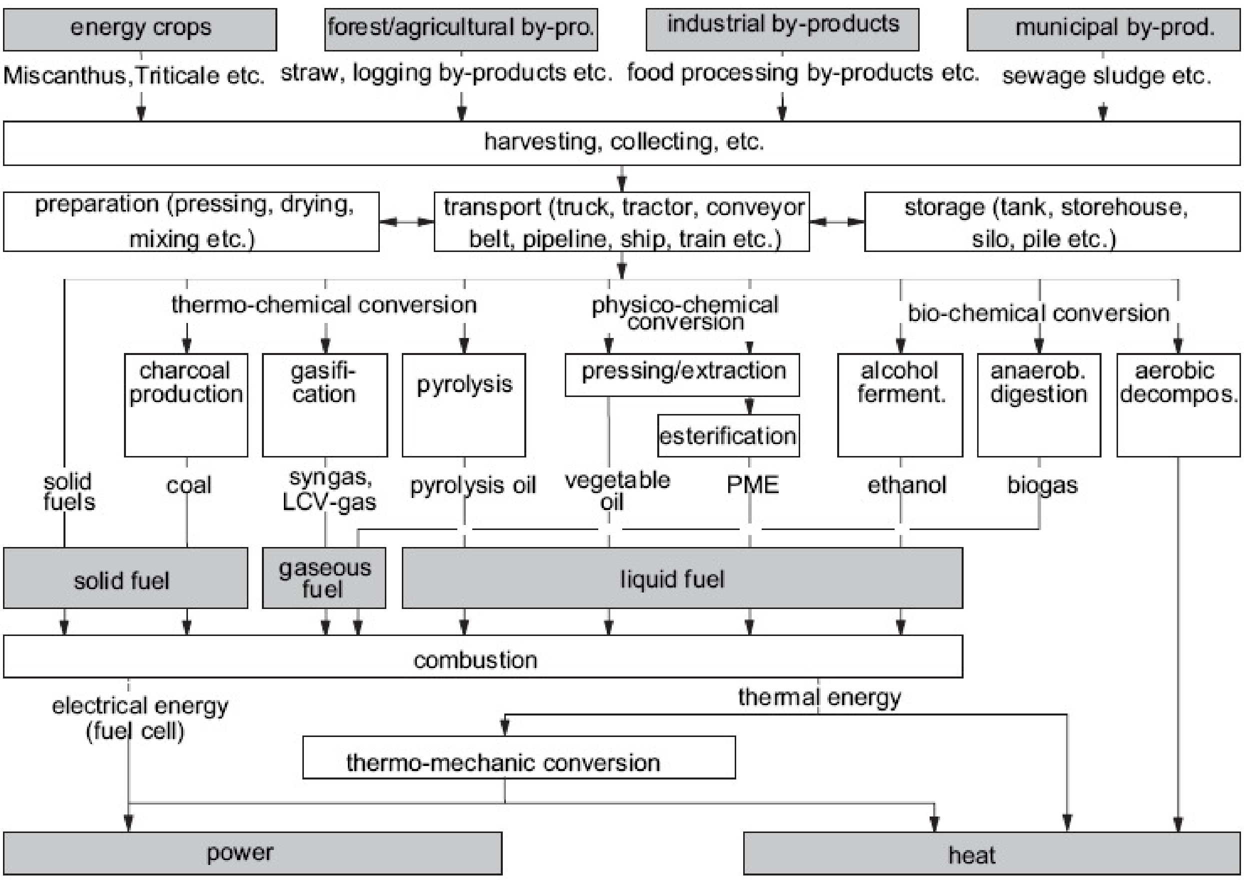


Figure 4.1: Possibilities to provide heat and/or power as well as fuels from biomass [25]

[25] Thraen et al.; UNIFIED BIOENERGY TERMINOLOGY; December 2004; p.12

The three main processes are thermo-chemical, physico-chemical, and bio-chemical conversion. The method of using biomass for combustion to receive heat is as old as mankind itself.
The second part of this paper will concentrate on gasification and primarily on the preparation of wood chips (drying) for this process.

Rising oil prices as well as the unsettled situation in the main oil-supplier countries have lead to increased investments in facilities for production of liquid bio-fuels.
The product from esterification which is PME (vegetable methyl ester) is known as Biodiesel, and it can be used in pure form or blended with petroleum diesel.
Alcohol fermentation and the production of ethanol are strongly promoted by the government of Brazil. It should become an alternative fuel to petroleum and lead to more independency from oil imports.

The biological-chemical processes listed in figure 4.1 can also be described in the form of a chemical equation:

Anaerobic digestion

- hydrolysis $\{C_6H_{10}O_2\}_x + x\ H_2O \rightarrow x\ C_6H_{12}O_6$ (4-1)
- acidification $x\ C_6H_{12}O_6 \rightarrow 3x\ CH_3COOH$ (4-2)
- methanation $3x\ CH_3COOH \rightarrow 3x\ CH_4 + 3x\ CO_2$ (4-3)

Alcoholic fermentation

- hydrolysis $\{C_6H_{10}O_2\}_x + x\ H_2O \rightarrow x\ C_6H_{12}O_6$ (4-4)
- fermentation $x\ C_6H_{12}O_6 \rightarrow 2x\ C_2H_5OH + 2x\ CO_2$ (4-5)

The biggest part of biomass used to generate ethanol are starch-laden crops such as corn or sugar-laden crops such as sugarcane.
If corn is used for the production of ethanol, the process will often require external energy input. Another unknown aspect for using corn as source is the price fluctuation which varies from year to year due to change of weather conditions, input costs and agricultural policy [8].
Brazil, as the largest ethanol producer in the world, uses sugarcane for this aim.

Since the costs of ethanol production out of corn are high in some countries, efforts have been made to use low-cost biomass such as wood or other herbaceous species for the conversion into ethanol. These sources are less expensive but more difficult in handling and more difficult to convert into ethanol as it is inedible for human beings. Wood and herbaceous biomass are referred to as lignocellulose and contain three components: cellulose, hemicellulose and lignin.

"*Cellulose is a crystalline lattice of long chains of glucose molecules. Its crystallinity makes it difficult to unbundled into simple sugars. Once they are produced, however, the sugar are easily fermented into ethanol. Hemicellulose consists of polymers of five-carbon sugar, such as xylose. Hemicellulose is easily broken down into simple xylose sugar, but these are difficult to ferment. Lignin is made up of phenols, not sugars, not sugars, and for practical purposes is unfermentable to ethanol.*"[26]

There are several ways and processes which have been tested and proposed for this kind of task.
Separate hydrolysis and fermentation (cf. figure 4.2) are a processes separating cellulose, hemicellulose and lignin, whereby after this step cellulose is treated with an acid or enzymecatalyzed hydrolysis process. As a consequence, cellulose is converted into fermentable glucose. Different by-products are coproduced from which the most valuable is furfural.

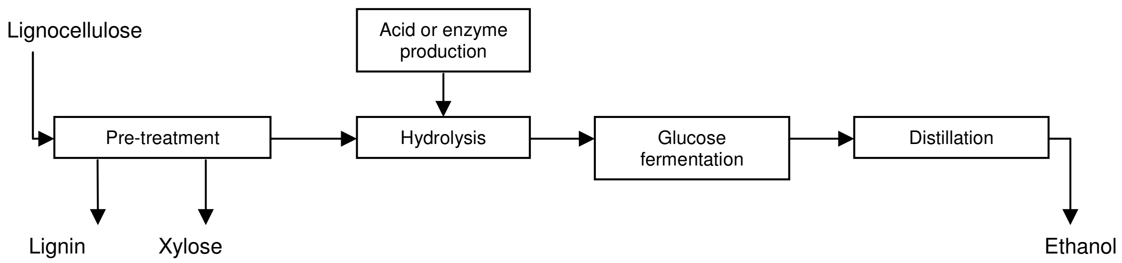


Figure 4.2: Separate hydrolysis and fermentation (SHF), using either acid or enzyme-catalyzed hydrolysis; source [8]

Simultaneous saccharification and fermentation (SSF) with an additional xylose fermentation is the second process (cf. figure 4.2.). In one step glucose is removed

[26] Larson; 1993; p. 615

by simultaneous hydrolyzing and fermentation which leads to improvements compared to the process described before (SHF), "(…) *because more complete hydrolysis of cellulose occur, at faster rates, and in one rather than two reactor vessels*." [27]

Another advancement of this process is the xylose fermentation, where 30 – 60 percent of total fermentable sugar in biomass are available [8].

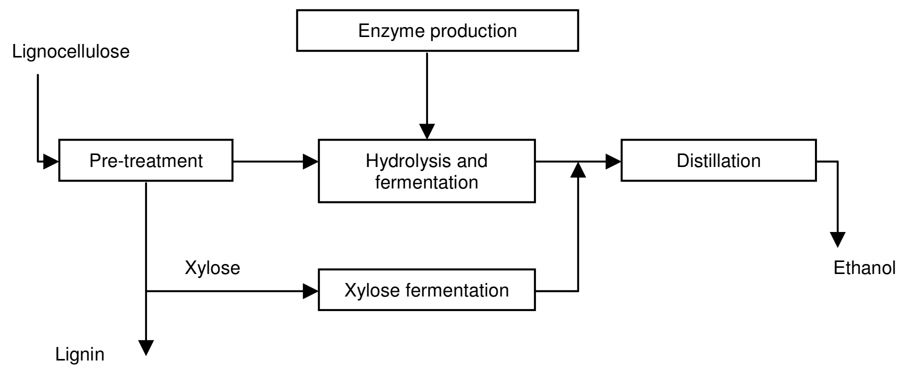


Figure 4.3: Simultaneous saccharification and fermentation (SSF) with additional xylose fermentation; source [8]

The next process combines different steps such as enzyme production, cellulose hydrolysis and glucose fermentation in the same reactor and is called direct microbial conversion (DMC). In the past, yields of both the SHF process and SSF process, which were specified above, were higher than of the DMC process. Unfortunately, the formation of undesirable products accompanied the production of ethanol.

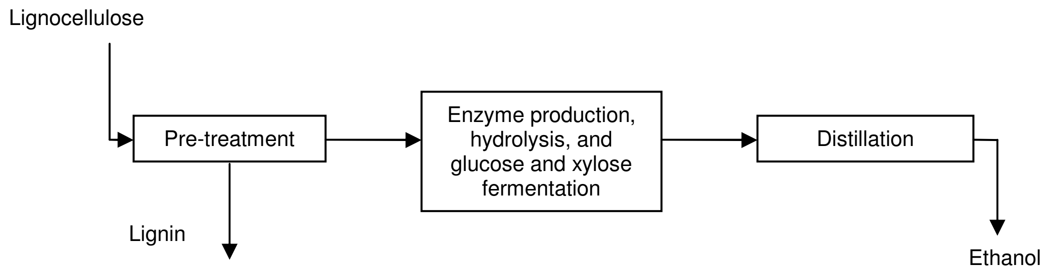


Figure 4.4: Direct microbial conversion (DMC); source [8]

Future advancements in biotechnology will probably change this outlook and improvements in efficiency and cost reductions are to be expected.

[27] Cf. Larson; 1993; p. 618

Another promising biomass end-product is hydrogen which is produced by gasification. Today the production of hydrogen is based on the use of fossil fuels, basically by means of natural gas reforming. Through the application of biomass, which is a low-cost fuel, it could be possible to generate hydrogen as a high-value end product. It can be used for chemical production, electricity and may also be used as fuel source. Biological and thermal conversion processes are currently being explored.

The block diagram below will show the production of hydrogen from biomass feedstock by means of gasification.

Biomass which is inserted into the gasifier must have a moisture content of 15 – 20 percent for better mode of operation. If the moisture content is higher, a dryer has to be interposed upstream.

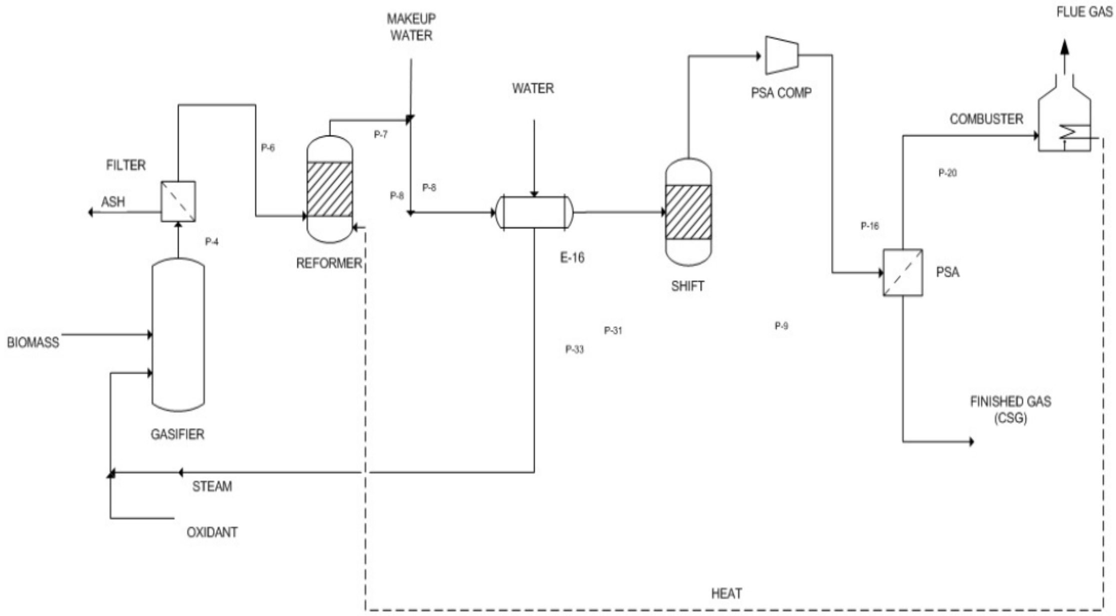


Figure 4.5: Hydrogen production by gasification of biomass with 10 – 20 percent moisture content [28]

In their report “Techno-Economic Analysis of Hydrogen Production by Gasification of Biomass” Francis S. Lau et al. compared three types of biomass for hydrogen production.

[28] Lau et al.; Final Technical Report Corrected Revision as of June 16, 2003; p. 8

	Bagasse	Switchgrass	Nutshell Mix
Heat Used in Reformer [GJ/h]	24.8	25.7	24.2
Heat Used in Dryer [GJ/h]	45.8	0	0
Heat Recovered from PSA Reject [GJ/h]	60.0	80.5	89.0
Heat Recovered from Reformer Stream [GJ/h]	19.1	8.1	5.3
Net Heat from the system [GJ/h]	8.5	62.9	70.1
Power Used in PSA Compressor [GJ/h]	6.97	8.20	8.45
Power Used for Air Separation [GJ/h]	5.90	5.10	4.10
H2 Product Heating Value [GJ/h]	186	220	230
Dry Biomass Feed Heating Value [GJ/h]	297	342	361
Cold Efficiency	0.628	0.644	0.637
Effective Thermal Efficiency	0.583	0.744	0.756
H2 / Dry Biomass [g/kg]	78.1	84.1	88.3

Table 4.2: Comparison of hydrogen production with different biomass feedstock; [8]

There are no significant differences in relation to cold efficiency between these three feedstocks, yet the results for the effective thermal efficiency differ. Bagasse for instance has a low value because its moisture level is higher in the beginning of this process and has to be dried, which can be seen from the heat usage in the dryer (cf. table 4.2).

Cold and effective thermal efficiency are for this calculation defined as follows:

$$\text{Cold Efficiency} = \frac{\text{Hydrogen Heating Value in the Product (HHV)}}{\text{Biomass Heating Value in the Feed (HHV)}} \tag{4-6}$$

Effective Thermal Efficiency (ETE)

$$\text{ETE} = \frac{\text{Hydrogen Heating Value in Product (HHV) + Net Heat from System}}{\text{Biomass Heating Value in Feed (HHV) + (Electricity Use / 0.35)}} \tag{4-7}$$

The cold efficiency gives the ratio of generated hydrogen per unit mass of feedstock [6].

As already mentioned before, hydrogen can be used to produce electricity power through fuel cells, which are large and stationary, or small local fuel-cells.
Other ways to produce electricity power from biomass are by means of prime mover. These options include the steam turbine, internal combustion engine, or gas turbine.

Below there will be represented two systems at which the first shows the “easiest” way to produce electricity from biomass. Biomass is burnt in a boiler and thereby produces pressurized steam which is expanded through a turbine to produce electricity. The system is designed not only to produce electricity but also to provide heat. For this purpose some steam would be extracted from the turbine.

Such systems of power plants use a technology which has been in use for 100 years and is therefore well known. The steam-Rankine cycle which is used is more efficient with higher peak pressure and temperature of the steam. The difference between power plants with coal as source and biomass power plants lies in the steam condition for the operating system. The latter operates with gentle steam conditions.

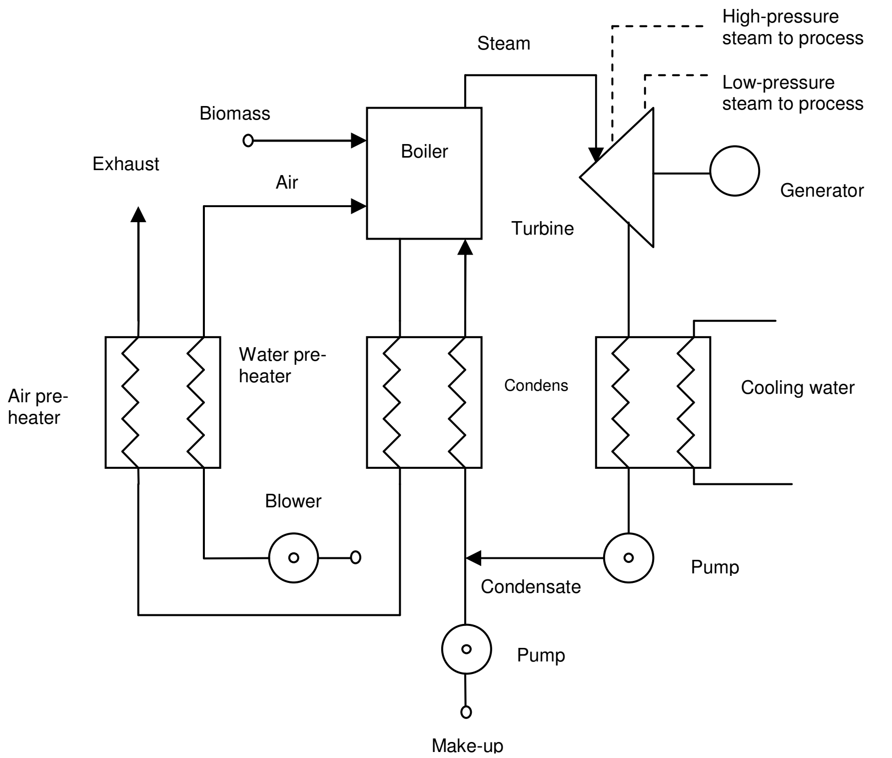


Figure 4.6: Biomass steam-turbine system for electricity generation; source [8]

The following block diagram will show a system by which biomass is gasified in a pressurized fluidized bed reactor in air, extracted from the gas turbine compressor.

Inside the gasifier the temperature reaches around 900°C. Hot gases have to be cooled in order to eliminate alkali vapours [29] (which will condense) and passed through gas cleaning filters (which could be damaged by the high gas outlet-temperature). After the gas has been cleaned it is burned in a gas turbine combustor. Exhausts from the turbine pass through a heat recover steam-generator and the steam is used in a steam-turbine system (cf. figure 4.6) for another electricity production [8].
The gas turbine systems operate with the Brayton-cycle which, compared to Rankine-steam cycles, can reach a higher thermodynamic efficiency because the peak cycle temperature is higher for gas turbines (1260°C) than for steam turbines (540°C).
One disadvantage of this system is that the gas turbine needs clean fuels which cause costs for filter installation. These filters operate at a temperature of 300-400°C. On the other side such systems are planned to convert biomass to electricity efficiencies of 40 – 45 percent, more than the double of the Rankine-cycles system [8].

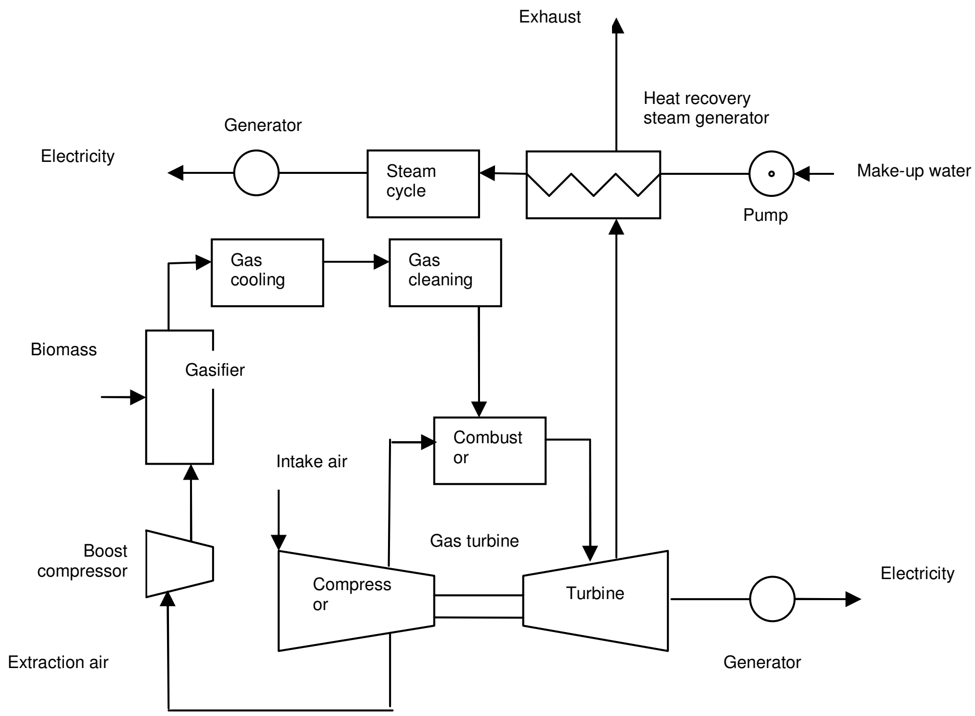


Figure 4.7: Biomass gasifier/gas-turbine combined cycle; source [8]

[29] Without cleaning it could lead corrodes of blade in the gas turbine.

4.2 Actual price dates for fossil energy

In order to see why an intensified investigation in the sector generation of energy from renewable sources' is observed, it is necessary to evaluate how the market will evolve regarding fossil fuels in consideration of the environmental influences. Products from biomass such as electricity, gas, hydrogen or liquid products have been too expensive in the past in order to be competitive with products from fossil fuel.

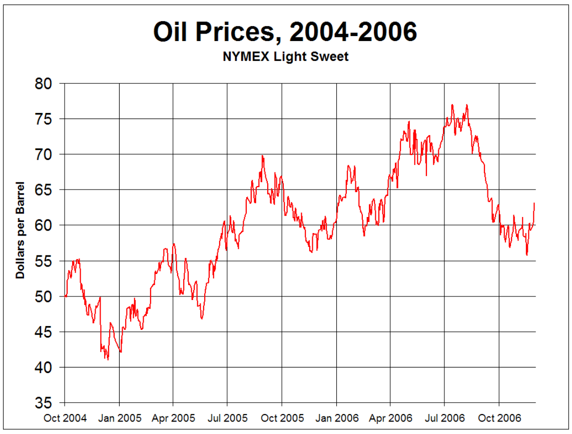


Figure 4.8: Price trend for oil 2004-2006 [30]

Although the price for barrel oil has decreased in the last few weeks, the long-term price will increase. One reason for this is the raised market demand for oil sources and the second reason is the lauder discussion of the Peak-Oil theory and the possibility that the future may see a reduced supply of oil. The situation is the same for natural gas and coal. It is expectable that the prices for natural gas and coal will also rise in the future although the proved resources are much bigger than those of oil.

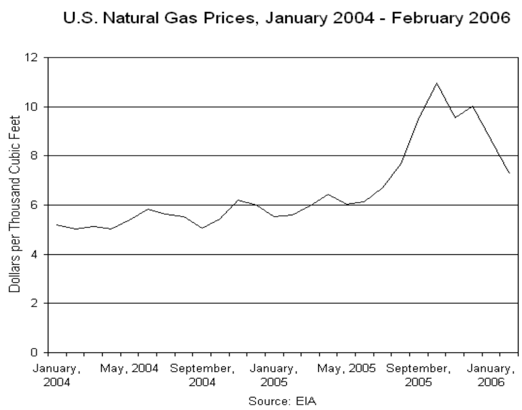


Figure 4.9: Price trend for U.S. Natural Gas; Jan.2004 to Feb.2006; source: EIA

[30] Cf. http://octane.nmt.edu/gotech/Marketplace/Prices.aspx

Coal will become more important in the future and will have an increased popularity, because of its large deposit. It is one of the most important sources to generate electricity world-wide and is also of great importance to the steel industry as a component in the reduction of iron ore.

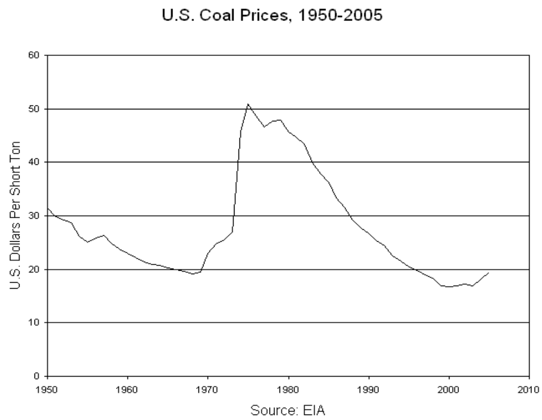


Figure 4.10: Price trend for U.S. Coal; 1950 - 2005; source: EIA

Figure 3.1. shows a price comparison of all sources. One can see that the price for renewable fuel has roughly been constant in the last years compared to the price for fossil fuels.

4.3 Comparison

Today biomass is primarily used for heat production and electricity generation. Direct combustion for heating and/or warm water supply is commonly used in household stoves. Also warm water/heating systems where more than just one house is connected to the heat-production facility and the thermal capacities can range from a few kW to several MW, are quite popular. The conversion efficiency for simple stoves which is traditionally used in developing countries varies from 8 to 18 percent and for high-end technology units up to 90 percent. As mentioned before, the easiest way to produce electricity from biomass is to burn it.
However, biomass power plants are limited in their size and compared to coal and nuclear steam-electric plants (500-1000MWe) rather small. Problems with fuel transport and strongly rising costs do not allow such a big construction of biomass power plants [8]. Comparing coal or natural gas power plants and biomass plants, the efficiency is the same in all systems.

Another positive aspect is that for the biomass sector further progression in the agricultural array and in terms of development of supply are expected. This would lead to decreased costs for biomass fuel and thus to reduced costs in electricity, heat and liquid fuel production.

In her paper Daniela Thraen evaluates the different ways of biomass conversion and their viability. The first part compares the feedstock and its best suitability for various conversion routes is discussed. Most of these conversion technologies need or are based on special-grown biomass. Also the aspect of conversion technology, which is separated into two fields, is discussed.

As a last point she looks at the cost-reduction potential for all systems. "*Based on availability of different feedstock, only gasification and pyrolysis seem to be promising options.*" [31]

	Charcoal prod. & use for heat production	Syngas production & elect. Generation	Pyrolysis oil prod. & use in engine	Vegetable oil prod. & transport. Use	Veg. Oil esterification & transport use	Alcohol production & transport use	Biogas production & elect. generation
Feedstock							
By-products	++	+++	+++				++
Energy Crop	+++	+++	+++	+++	+++	+++	+
Conversion Technique							
Technology	+++	++	+	+++	+++	+++	++
System Technology	+++	+	+	+++	++	++	++
System Aspects							
System Integration	+	+++	+++	+	+++	+++	++
Environmental Benefits	++	+++	+++	+++	+++	+++	++
Costs	++	+	+	+	+	+	+
Cost Red. Potential	+	+++	+++	+	+	+	++

Evaluation: + less promising; ++ promising; +++ very promising

Table 4.3: Comparison of biomass conversion routes [32]

The production of fuels such as methanol or hydrogen is strongly forced by the government's policy, as the previously mentioned example of Brazil shows. Developments of processes which use wood or herbaceous as fuel for ethanol are leading to more opportunities also for countries where cheap fuel like sugarcane is not available.

[31] Thraen; 2004; p. 12
[32] Daniela Thraen; UNIFIED BIOENERGY TERMINOLOGY; Dec. 2004; p. 13

The majority of methanol and hydrogen which is produced today comes from natural gas. For future consideration also coal is taken into account as a long-term feedstock.

Eric D. Larson made a comparison of the conversion efficiencies of methanol and hydrogen from biomass with coal and natural gas. Biomass and coal have a comparable efficiency, only if compared with natural gas it is significantly lower.

5. Other renewable energy suppliers

5.1 Photovoltaics

5.1.1 Efficiency and solar radiation

"Namely the first real solar cell was made (…) by the engineer Daryl Chapin, the chemist Calvin Fuller and the physicist Gerald Pearson of the Bell Labs in New Jersey USA (…). It was a few cm²-sized silicon wafer device, that had a terrestrial solar power conversion efficiency of 6%." [33]

This new technology has quickly been adopted for aerospace activities. Figure 5.1 shows the evolution of cell efficiency since their first production. The rising efficiency and the development of new systems are shown. This evolution will probably not change in the near future.

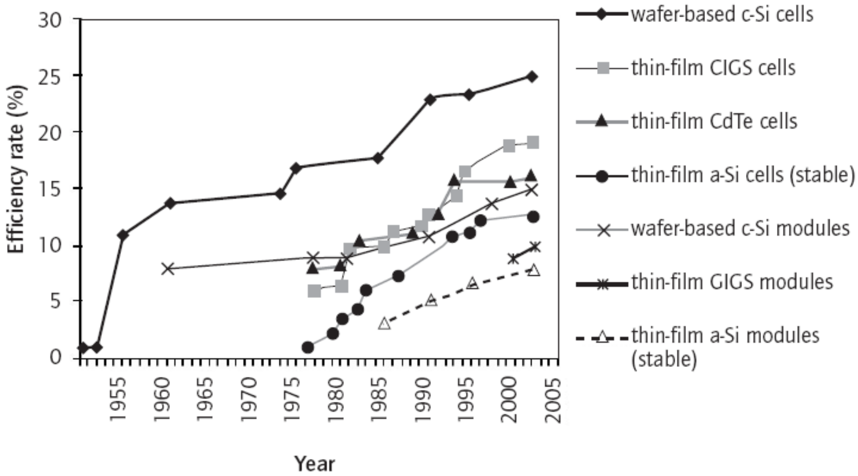


Figure 5.1: Evolution of cell efficiency; [34]

In order to describe the efficiency of a solar cell it is necessary to consider more than one value. Typical commercial solar cells are on metal-semiconductor Silicon (mc-Si) basis and they currently have the general conversion efficiency of 12 percent. From the economical side it has to be said that solar cells with the highest efficiency are not always the most economical. Comparing two solar cells with different efficiencies

[33] Cf. Willeke Gerhard P.; THE CRYSTALLINE SILICON SOLAR CELL – HISTORY, ACHIEVEMENTS AND PERSPECTIVES; Presented at the 19th European Photovoltaic Solar Energy Conference

[34] Cf. OECD; Renewable for power generation; 2003 Edition; p. 64

it can easily be the case that one of them has a higher efficiency but the production costs are several times higher than the production costs of a standard solar cell.

Other important criteria which are used in order to describe a solar cell are material, thickness and efficiency. An overview of the most common solar cells and some less frequently used ones is given in the table below.

Material	Thickness	Efficiency %	Colour
Monocrystalline Si solar cells	0,3 mm	15 – 18	Dark blue, black with AR coating, grey without AR coating
Polycrystalline Si solar cells	0,3 mm	13 – 15	Blue with AR coating, silver-grey without AR coating
Polycrystalline transparent Si solar cells	0,3 mm	10	Blue with AR coating, silver-grey without AR coating
EFG	0,28 mm	14	Blue, with AR coating
Polycrystalline ribbon Si solar cells	0,3 mm	12	Blue, with AR coating, silver-grey without AR coating
Apex (olycrystalline Si) solar cells	0,03 to 0,1 mm + ceramic substrate	9,5	Blue, with AR coating, silver-grey without AR coating
Monocrystaline dendritic web Si solar cells	0,13 mm incl contacts	13	Blue, with AR coating
Amorphous silicon	0,0001 mm + 1 to 3 mm substrate	5 – 8	Red-blue, Black
Cadmium Telluride (CdTe)	0,008 mm + 3 mm glass substrate	6 – 9 (module)	Dark green, Black
Copper-Indium-Diselenide (CIS)	0,003 mm + 3 mm glass substrate	7,5 – 9,5 (module)	Black
Hybrid silicon (HIT) solar cell	0,02 mm	18	Dark blue, black

Table 5.1: Overview of solar cells [35]

The term for the energy conversion efficiency of a solar cell is defined as:

$$\eta = \frac{P_m}{E \bullet A_c} \qquad (5\text{-}1)$$

Where η is the energy conversion efficiency, P_m is the ratio of (V_{max} x I_{max} [in W]). The equation is divided by the light irradiance input E [W/m^2] under (standard test conditions) and the surface area of the solar cell A_c in [m^2]. The performance of the solar cell and the photo conversion efficiency against solar radiation is plotted in figure 5.2.

[35] Cf. http://www.pvresources.com; (01.2007)

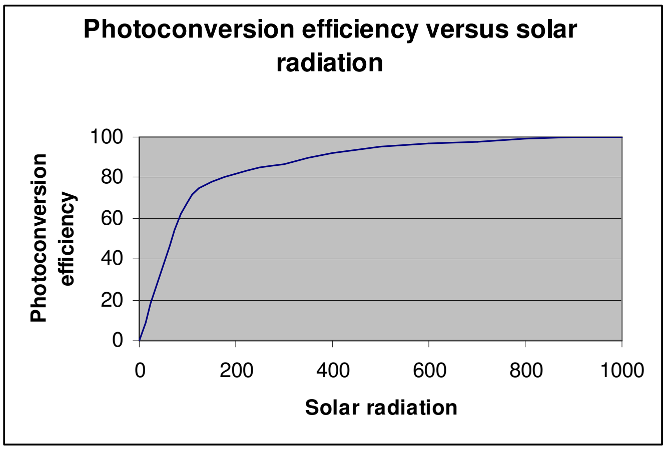


Figure 5.2: Photo conversion efficiency versus solar radiation [36]

The power output of a solar cell depends on the temperature. Higher cell temperature leads to lower power output and thus to lower efficiency. The degradation of the solar cell efficiency factor is around 10 percent for 25 years. Other factors which could have effects on the efficiency or output of solar cells are surface contamination, shadowing from plants which have grown to much and yellowing of the surface material.

5.1.2 Installation costs

Many loan programs and the financial incentives and the ability to sell the extracted electricity to the public grid have had a great influence on the annually increasing demand for solar cell technology in the last years.
The costs for solar cell modules have increased in the last years as well, although producers have managed to decline their own manufacturing costs. It traces back to the fact that the price for silicon has increased significantly within the last years.

The costs for a PV system are measured in price-per-peak-watt (EUR/Wp). (Peak Watt) is defined as the power at standard test conditions (solar insolation 1000 W/m^2, AM of 1.5 and temperature 25℃). [36]
Almost all suppliers offer an online calculation for the installation and module cost. The market leader of solar systems is the company Sharp (2006) with a “(…) *market share of 26 per cent*(…)” [37].

[36] Cf. http://www.pvresources.com; Based on studies made from 1996 to 2000 (01.2007)

In order to calculate the economical efficiency of a PV system, the following important parameters have to be considered; energy pay back time, buy back rates and the total costs of installing.

Installed PV-systems can be integrated for domestic use or be grid-tied, which represents the largest growth area.

<table>
<tr><th></th><th>System power</th><th>Installation costs</th></tr>
<tr><td rowspan="2">Off grid</td><td>100 - 500 Wp</td><td>14 - 30 EUR/Wp</td></tr>
<tr><td>1 - 4 kWp</td><td>10 - 15 EUR/Wp in developed countries, 30 - 40 EUR/Wp worldwide</td></tr>
<tr><td rowspan="3">On grid</td><td>1 - 4 kWp</td><td>7 - 15 EUR/Wp</td></tr>
<tr><td>10 - 50 kWp</td><td>7,50 - 20 EUR/Wp</td></tr>
<tr><td>> 50 kWp</td><td>up to 14 EUR/Wp</td></tr>
</table>

Table 5.2: PV-systems installation costs [36]

In the year 2003 the installation costs of 1 kW were set from 4500€/kWp to 6500€/kWp [37]. Other sources provide the following equipment prices for Polycrystalline modules (manufacturing costs): ~$2.000 / kWp and for Polycrystalline modules (commercial prices): from $3,490 up to $5.100 / kWp (8 m²/kWp). Additionally, some installation costs are incurred which amount from $600 up to $2.000 / kWp (self-construction: from $100/kWp up to $400 / kWp), and if the system has to be grid-tied an inverter which costs ~$400 /kWp is necessary [38].
The amount of electricity generated by photovoltaics at various locations is:

Southern Germany:	~ 900 - 1130 kWh per kWp per year
Italy, Sicily:	~ 1800 kWh per kWp per year
South Spain:	~ 1800 kWh per kWp per year
China, Takla Makan:	~ 1840 kWh per kWp per year
U.S.A., Great Basin:	~ 1930 kWh per kWp per year
Spain, Canary Islands:	~ 2000 kWh per kWp per year
U.S.A., Hawaii:	~ 2100 kWh per kWp per year
Africa, Sahara:	~ 2270 kWh per kWp per year

[37] Cf. www.prextra.sharp-eu.com (01.2007)
[38] http://en.wikipedia.org/wiki/Photovoltaics

Australia, Great Sandy: ~ 2320 kWh per kWp per year
Middle-East, Arabia: ~ 2360 kWh per kWp per year
South America, Atacama: ~ 2410 kWh per kWp per year

Until last year costs/kWh were several times higher than for conventional coal or gas power plants. "*Grid parity is already reached in some regions. This means photovoltaic power is equal to or cheaper than grid power.*" [39] This is the case when electricity is produced by use of diesel fuel. Such is the situation in Hawaii as well as on other islands.

As already mentioned, many governments have introduced new programs to intensify the production of electricity from renewable sources and make it competitive to fossil ones. A small overview of the most significant incentive programs will be given below.

Germany:

Feed-in tariffs:

Roof mounted <= 30 kWp : EUR 0.5180/kWh
Roof mounted 30 kWp to 100kWp: EUR 0.4928/kWh
Roof mounted over 100kWp: EUR 0.4874/kWh
Facade integrated as above + EUR 0.0500/kWh
Field installation EUR 0.4060/kWh

Contract duration 20 years, constant remuneration! New contracts will be 5 percent lower in value in 2007 (6.5 percent for field installations)

Italy:

The legal framework is a decree issued by the Ministry of Industry on 5th August 2005.

Feed-in tariffs:

at least EUR 0.445/kWh (too many variants to list here)

Contract duration 20 years, linked to inflation

California:

Starting on 1st January 2007

Feed-in tariffs and investment subsidies:

[39] Cf. www.pvresources.com; 01.2007

Systems >100 kWp: $0.38/kWh

Systems <100 kWp can choose either $2.50/kWp or $0.38/kWh

Additional investment subsidies available as federal tax credits.

Contract duration 5 years, constant remuneration

(Note: All data from[40])

5.1.3 Research and Development

In order to make PV-technology more competitive to other renewable and fossil technologies, the costs have to be reduced as they are relatively high at the moment. The strongly increased demand for PV-systems has lead to a shortage of basic component silicon, and thus to high prices for panels. Developers have started to use other materials and thinner silicon layers in order to keep down the costs.
Figure 5.3 will show the cost reduction which has been achieved from 1983 to 2002.

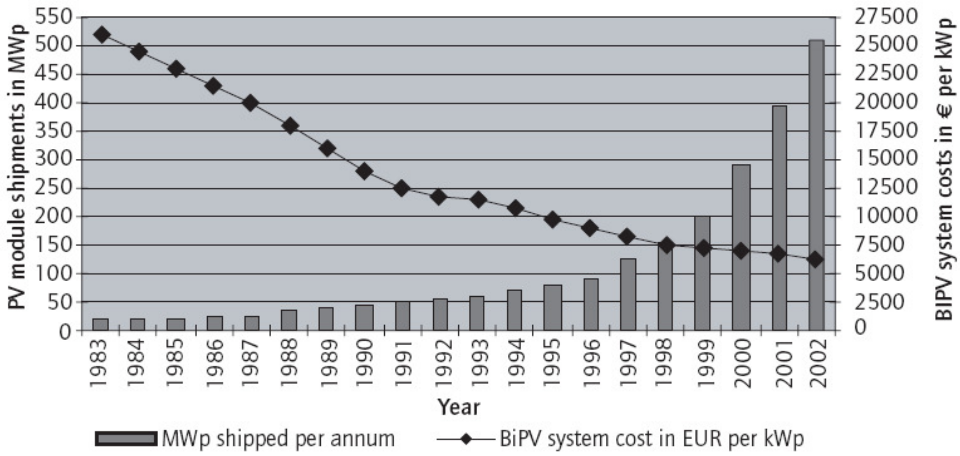


Figure 5.3: Annual world PV module production and building-integrated PV system costs [41].

It may be expected that the efficiency will increase and if the progression for PV-systems in figure 5.1 is considered, new technologies might be expected in the future. An increased cell efficiency of 2 to 4 percent implies an efficiency gain of 20 percent for established crystalline silicon technologies and up to 40 percent for thin-film technologies [21].

[40] http://en.wikipedia.org/wiki/Photovoltaics; (01.2007)
[41] Cf. OECD; Renewable for power generation; 2003 Edition; p. 64

The PV module accounts for around 60 percent of the total costs for grid-connected systems. The remaining 40 percent cover up for inverter, mounting structure, installation and planning. Improvements regarding these components, mainly in terms of increasing efficiency and extension of lifetime, would contribute to a cost reduction. As observed in the past, a common inverter ranging from 1,5 kW to 3,3 kW had an efficiency of around 85 to 90 percent, whereas now more than 90 percent and often even 95 percent are reached. Thus grid-connected and stand-alone systems could benefit from these improvements. Another possibility would be the standardisation of such systems which would have the effect that PV-systems could be used for instance as common building materials.
There are still technologies which are not ready for the market and are only run in laboratory or tested as pilot constructions. Newly designed arrangements of PV-surfaces could lead to an increased recovery of sun rays and thus to higher efficiency.

An often discussed issue connected with PV is the fossil energy need for the production of such systems. Both the increase of life time of PV modules and the reduction of energy during the manufacturing process are key future-goals [21].

PV power plants have been installed around the world and in the past they rather operated for research purpose. Since the efficiency of solar systems and the demand for clean energy have increased, the sales of energy plants have become more frequent.

DC Peak Power	**Location**	**Description**	**MWh/year**
12 MW	Gut Erlasee, Germany	1408 SOLON mover	14000 MW·h
11 MW*	Serpa, Portugal	52,000 solar modules	n.a.
10 MW	Pocking, Germany	57,912 solar modules	11500 MW·h
6.3 MW	Mühlhausen, Germany	57,600 solar modules	6750 MW·h

Table 5.3: World largest PV power plants [42]

[42] Cf. Sources: http://www.pvresources.com/en/top50pv.php; * Under construction, as of 2006

Table 5.3., shows that the largest plants are in Germany where the average insolation is lower than in some South European countries (cf. appendix 2). This situation has certainly been provoked by government subsidies and its strong focus on renewable energy.
A plant in Australia, which will not come into service until 2008, is expected to be 154 MW when it is completed in 2013 [43].

5.2 Wind power

5.2.1 Efficiency and possibility

A small part of solar energy is converted into wind energy. As shown in figure 2.1 regions around the equator are more heated than regions around the poles. Most of this wind energy can be found at high altitude where the movements of the wind are from the equator to the pole.

The decision which turbine size is best and most economical depends on the available wind power density (cf. table 5.4).

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density (W/m^2)	Speed m/s (mph)	Wind Power Density (W/m^2)	Speed m/s (mph)
1	0	0	0	
	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1,000	9.4 (21.1)	2,000	11.9 (26.6)

Table 5.4: Classes of Wind Power Density at Heights of 10 m and 50 m; source: EIA

[43] Cf. http://www.cosmosmagazine.com/node/800; (01.2007)

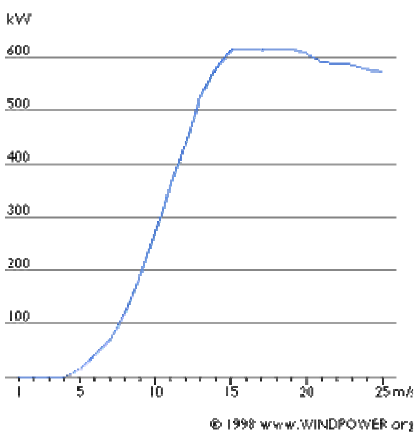
"*The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.*"[44] The density of air decides about kinetic energy and therefore the heavier the air the more energy is received by the turbine. Another component is the rotor area which decides how much wind energy is converted to electricity. The area increases with the square of the rotor diameter. This is one of the reasons for choosing a bigger wind turbine, as a to-times larger turbine produces four times more energy.

The amount of wind power can be described as formula as follows:

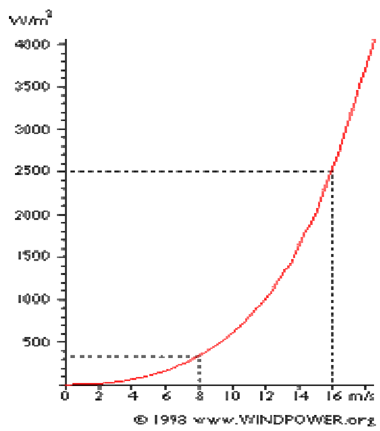
$$P = 0,5 * \rho_{air} * \pi * R_{rotor}^2 * v_{wind}^3 \qquad (5\text{-}2)$$

According to Betz' Law (German Physics) it is possible to convert only 59 percent of kinetic wind energy to mechanical energy by using a wind turbine.

A wind turbine extracts energy from wind, and thus makes it slow down. The perfect wind turbine would slow down the wind to 2/3 of its original speed. Figure 5.4. shows how important the wind velocity is for disposable energy; graph a) shows a power curve and b) shows wind speed against power per square meter. Both graphs are of a typical Danish 600 kW wind turbine.



a)



b)

Figure 5.4: Wind speed connected to the comprised power in W/m²; sources[45]

[44] Cf. http://www.windpower.org/en/tour/wres/enerwind.htm; (01.2007)
[45] Cf. www.WINDPOWER.org (01.2007)

The effect of slowing down the wind has an influence on the line-up of such power plants. On the one side placing the wind turbines as far as possible from each other would ensure increased energy output, but on the other side land use and the costs for connection to the grid demand shorter distances. Such problems with the arrangement are called the park effect.
It is difficult to find the ideal positioning of the tower, but roughly it can be said that the intervals of rows should be 8 to 12 [33] or 5 to 9 [35] of rotor diameter in the prevailing wind direction, and 1,5 to 3 [33] or 3 to 5 [35] of rotor diameter in the crosswind direction. Therefore, the use of land must be studied in detail in order to determine the number of turbines and their size to extract the maximum energy from the farm. Efficiency losses provoked by the so-called park effect arise in around 5 percent. Other considerations which have to be done are:

The optimal size of the turbine: with a rising size the costs per MW are lower and they occupy less land area but if there are few larger machines on the field, the breakdown of one would stronger reduce the MWh energy output (capacity factor) than a smaller machine.
The capacity factor is defined as follows: "(…) *its actual annual energy output divided by the theoretical maximum output, if the machine were running at its rated (maximum) power during all of the 8766 hours of the year* (…)" [46] and not always is the higher capacity factor the more economic one.
In practice, this factor can vary from 20 to 70 percent and is mostly around 25 to 30 percent.

Another problem which occurs is that wind power is dependent on wind fluctuation. The energy output varies every day and is typically higher during the day and lower during the night when the wind is less strong. For larger machines higher costs for electrical filtering of the power and voltage fluctuation emerge. Such variances could have quality effects on power.

5.2.2 Installation costs

Installation costs include not only the turbine itself but also the transportation, foundation, road construction, transformer to convert the energy in capable, for the local grid and electricity. A comparison between three turbine sizes and their cost subdivision for equipment components will be given in figure 5.5.

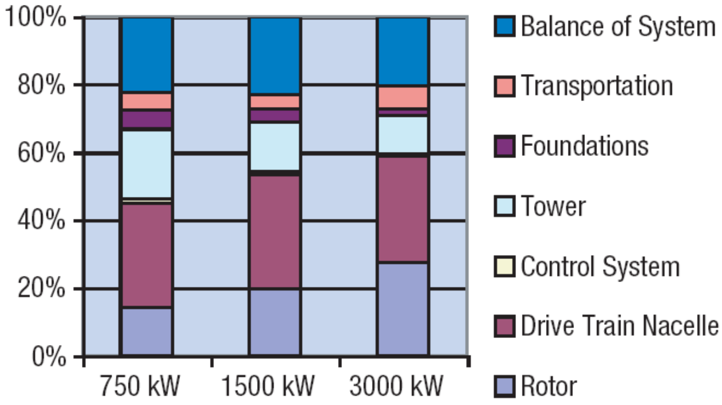


Figure 5.5: Cost allocation for three different turbine sizes [46]

Blade and rotor comprise up to 25 percent of a wind turbine's total cost and the drive train nacelles comprises another 30 percent. Future generation of wind turbines tend towards a bigger size of >1000 kW.

In order to keep down the costs, it is advisable to connect as many turbines as possible under consideration of the local grid capacity. As already mentioned, a bigger turbine is not always an economic one, especially in areas with little wind. Plotting the investment costs for different sizes of wind turbines results in a typical chart which is referred to as the banana look.

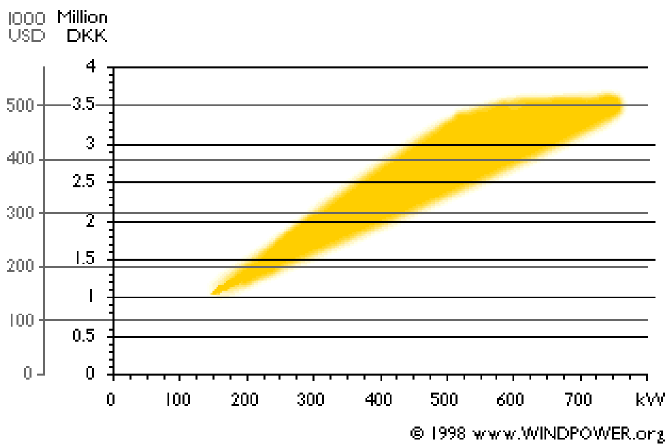


Figure 5.6: Development of costs for wind turbines [47]

[46] Cf. Federal wind program highlights; U.S. Department of Energy - Energy Efficiency and Renewable Energy; 2004; p.8

[47] Cf. www.WINDPOWER.org (01.2007)

The above shown figure provides give an overview of the costs for wind turbines in Denmark. The range of different available equipment raises for bigger turbines and with it also the price gap. One reason for different prices could be the desired tower height or rotor diameter. In areas with little wind the turbines demand a bigger rotor diameter which makes them more expensive. In comparison to Photovoltaic the price for one kWe (PV~ 5000USD) is lower and lies around 1000 USD/kWe. This situation concerns large, modern wind farms while for single turbines and smaller wind farms the costs will be a little higher.
Such wind turbines also have maintenance costs which include a first fixed amount for regular service and further amounts for maintenance repairs. The amount per kWh of output are around 0,01 USD/kWh. Thereby, the maintenance-repair costs are influenced by local climatic conditions and of course the quality of the turbine itself. Offshore wind turbines are for instance less exposed to wind turbulences at the sea side and therefore last longer. The actual lifetime of a wind turbine is around 20 years or 120 000 hours of operation. After this period one has to decide about extending them through overhaul or replacing them by a new one, if economical [35].

There is a difference between offshore (sea side) wind turbines and onshore (land) turbines. One reason why this type of energy extraction becomes more economic is that the foundation costs have decreased significantly. Offshore wind parks use larger turbines with an output of >1000 kW or more. Because of stronger and constant wind at the sea side, the energy output is higher and the longer lifetime (around 30-50 years) minimizes the costs/kWh which are equal to those of onshore wind turbines.

How the costs of electricity depend on the wind speed and height location of the turbine will be shown in the figure below. The graph presents the cost trends for hub heights at 10 meters and at 50 meters for a 600 kW turbine.

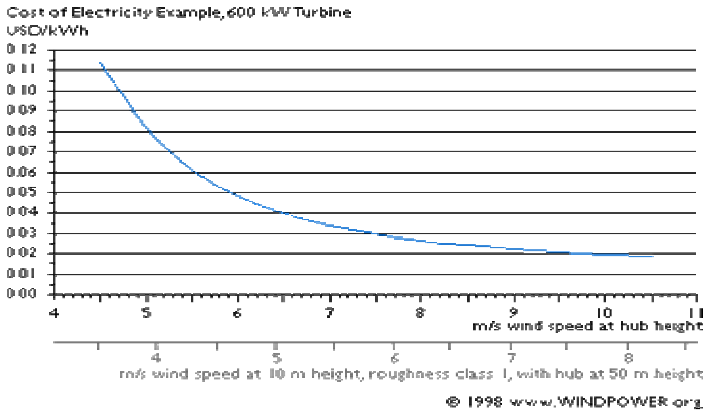


Figure 5.6: Costs of electricity example, 600 kW Turbine [48]

Figure 5.6. shows that low electricity costs are not reached until a defined wind speed. Also the hub height has a great influence and therefore height should be considered in the beginning, as an additional metre of tower will cause around 1 500 USD extra expenses.

5.2.3 Trends and future developments

The cost trend for the production of electricity shows that there has taken place a considerable decline during the last twenty years. From 1982 to 2002 a declension of about 33 US cent/kWh has been recorded. A reduction of costs will also take place in the future, but certainly not in such dimensions.

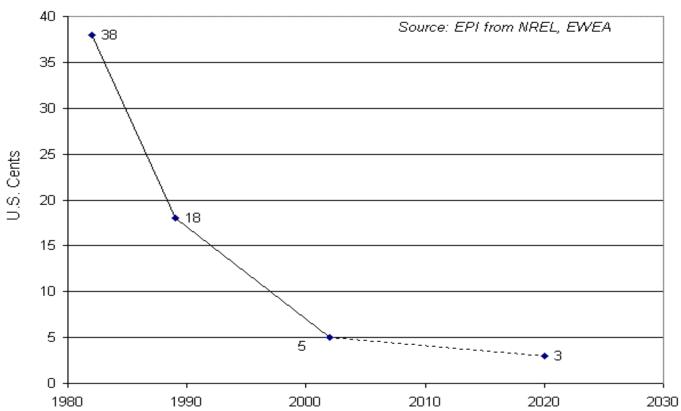


Figure 5.7: Average cost/kWh of wind generated electricity from 1982 to 2002 and an estimation up to 2020. [49]

[48] The example is for a 600 kW wind turbine with a lifetime of 20 years; investment = 585,000 USD including installation; operation & maintenance cost = 6750 USD/year; 5% p.a. real rate of interest; annual turbine energy output taken from power density calculator using a Rayleigh wind distribution (shape factor = 2). Cf. www.WINDPOWER.ORG

This means that the development in the field of wind-power energy supply has already advanced and only small improvements are awaited in the future. In some European countries, like Denmark, there are almost all onshore areas already utilized. As already mentioned before, winds at the sea side are more constant which means that there are less turbulences and this allows the establishment of bigger turbines. The lower cost per kWh also leads back to the application of bigger turbines which become cheaper through developments in this field.
As the market share of generations of wind turbines in Denmark shows (cf. figure 5.8), the trend between 1978 to 1998 went away from small turbines with power output of 22 to 33 kW to turbine sizes of 750 kW. The most utilized turbine size at the moment is a 1000 kW machine for which the offshore application tends to bigger sizes.

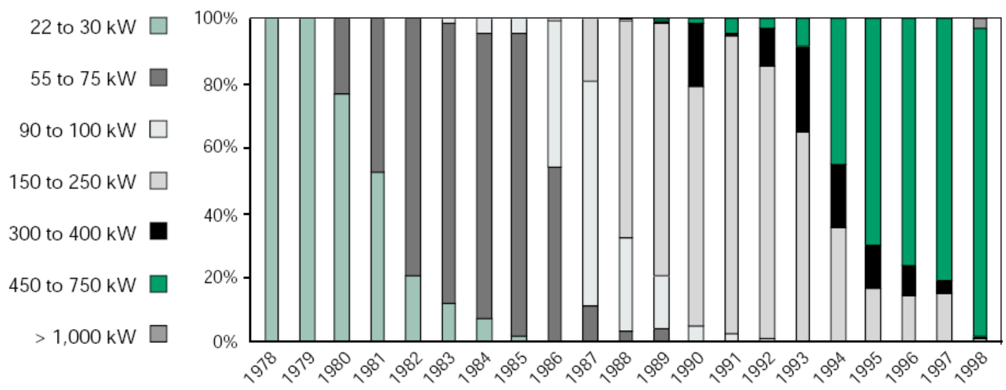


Figure 5.8: Market share of Generation of wind turbines in Denmark [50]

Another interesting trend is the connection of cost and capacity of wind power. With the dropping costs for generating electricity automatically, the installed amount of wind power turbines increased.

Required improvements or optimization have to be done for higher grid reliability and the problem with intermittency of wind. Both problems are connected to each other and affect the reliability of the grid.

[49] Cf. http://www.earth-policy.org/Updates/2006/Update52_data.htm
[50] IEA Market & Policy Trends in IEA Countries (2004); p.82

5.3 Solar Heat

5.3.1 Efficiency and possibility

Solar heat power can be used directly to produce heat or electricity. The use of solar energy for warm water heating (active solar) is already quite common. Solar collectors are usually attached to the roofs of houses and connected to the hot water boiler.

In cases where the sunlight is used to produce electrical power, the technology is called concentrating solar power (CSP). This technology makes use of direct sunlight which is concentrated several times to reach higher energy densities. This concept facilitates the achievement of a higher temperature which is absorbed by material's surface. These kinds of power plants are best applicable in areas with high direct solar radiation. A "(…) *require[d] minimum of yearly direct insolation is about 2000 kWh/m², but insolation of 2,500 kWh/m2 is more likely to favour competitiveness* (…)" [51]

Other important factors are the land costs, the fact that SEGS (Solar Electricity Generation System) plants need about 2 hectare to provide MWe and costs for construction and operation [23].

CSP technologies can only be applied in those parts of the world where the insolation is strong enough. The world map in figure 5.9 will show which continental parts are suitable for the installation of power plants.

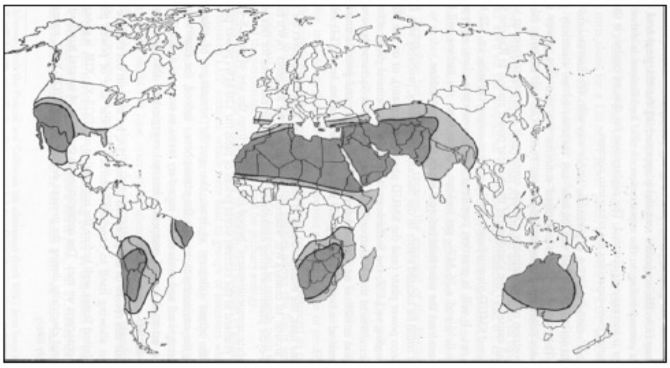


Figure 5.9: The suitable areas in the world for CSP use [52]

[51] Cédric; IEA; 2004; p.11
[52] Cédric; IEA; 2004; p.12

As the above figure shows, the sunniest European countries are not the best places and can just be rated as a second choice. The best places with the right amount of direct solar radiation are in Africa, the Middle East, Australia and some parts of North and South America.
Three kinds of CSP systems are used:

- Dishes
- Towers
- Troughs

These techniques have different advantages and disadvantages. Currently, the most used CSP technology is the parabolic which still has considerable potential for improvement. Probably even greater potential for improvements have the not yet fully developed Power tower and dishes although these two systems reach higher temperatures and offer higher conversion efficiencies [23].

	Parabolic trough	Power tower	Dish/engine system
Peak efficiency	21 %	23 %	29 %
Annual capacity factor (without and with thermal storage)	24 %	25 %- 60 %	25 %
Net annual efficiency	13 %	13 %	15 %

Table 5.5: Peak Efficiency and annual capacity factors for the three CSP Technologies, 2000 [21]

Solar energy is more widely used for water and/or home heating. "*The efficiency of a solar collector is defined as the quotient of usable thermal energy versus received solar energy. Besides thermal loss there always is optical loss as well.*" [53]
In order to select an ideal collector, a high conversion factor and a low thermal loss factor have to be present.

[53] Cf. www.earth-policy.org

Type of Collector	Conversion Factor	Thermal Loss Factor in W/m² °C	Temperature Range in °C
Absorber (uncovered)	0,82 to 0,97	10 to 30	up to 40
Flat-plate collector	0,66 to 0,83	2,9 to 5,3	20 to 80
Evacuated-plate collector	0,81 to 0,83	2,6 to 4,3	20 to 120
Evacuated-tube collector	0,62 to 0,84	0,7 to 2,0	50 to 120
Reservoir collector	about 0,55	about 2,4	20 to 70
Air collector	0,75 to 0,90	8 to 30	20 to 50

Table 5.6: Conversion factor, thermal loss and temperature range for different kinds of collectors [54]

The thermal loss factor is given in W per m² collector surface, sometimes it can be expressed as the k-value. The value depends on the temperature difference between the absorber and its surrounding.

In order to choose the right solar collector it is important to know about the desired temperature range of the material to be heated. Evacuated tube collectors have a high temperature range and could be suitable for all applications but they are expensive and therefore a normal absorber could be sufficient to heat for instance the swimming pool.

5.3.2 Installation costs

Installation costs for CSP power plants are difficult to estimate because they depend on a multitude of factors. Some types are in usage just as pilot or demonstration plants, therefore the investment costs are often only a rough estimation. Technology factors such as system performance, component size, power cycle or logistics factors like plant size, irradiation and land cost have a great influence on the overall costs [21].

	Parabolic trough (SEGS type)	Power tower (Solar Two)	Dish/engine system (Stirling)
Investment cost [Euro/kW electrity]	2800 - 3200	4000 - 4500	10000 - 12000
Electricity generation cost [Euro/kWh]	0,12 - 0,15	0,15 - 0,2	0,2 - 0,25

Table 5.7: Investment and Generation Costs for CSP Technologies

[54] Cf. www.solarserver.de

As mentioned before, some values in table 5.7 are only rough estimations. Comparing solar heat with other renewable technologies, costs for operation and maintenance are relatively high and amount from 10 to 15 percent of all costs, whereas CSP-plants are intended to have a lifetime of 20 to 30 years [21].

Such solar plants depend very much on the irradiation and the electric output and are "(…) *roughly proportional to the incident light onto the active area*" [55].

Different from this situation is the collector sector, where many manufacturers are available on the market. The specific costs are an important factor for the choice of the solar collector. In OECD report (Renewable for power generation; Status & Prospects (2003 Edition)) the prices for evacuated-tube collectors are stated from 511,29 to 1278,23 Euro /m² collector surface prices for flat-plate collectors range from 153,34 to 613,55 Euro /m² and the cheapest plastic absorbers cost from 25,60 to 102,26 Euro /m².

5.3.3 Trends and future developments

The limitation factor for this type of energy plant is the needed adequate solar irradiation of >1700 W/m². Looking on the land needs one can see that "(…) *centralised CSP plants require a significant amount of land that typically cannot be used concurrently for other purposes. A study for the U.S. State of Texas showed that land use requirements for parabolic trough plants are comparable to those of other renewable technologies such as wind or biomass, and lower than fossil resources when mining and drilling are taken into account*."[56]
A stronger cooperation between countries having a lot of experience with CSP power plant and countries which have the sunniest areas on the earth like Africa, Asia or Middle East could give a great opportunity to build new CSP power plants with high efficiency.

The potential for cost reduction is great. On the R&D field, improvements could lead to optimised components and subsystems. Progresses on reflectors and receivers, thermal-storage capability and heat transfer fluid, are promising too. Another way to

[55] Market & Policy Trends in IEA Countries; 2004; p.83
[56] Market & Policy Trends in IEA Countries; 2004; p.85

drop the costs is to build bigger components in order to enlarge the power plant size. "*Studies have shown that doubling the size of a trough solar field reduces the capital cost by 12-14%.*" [57]
Mass production could lead to a reduction from 15 up to 30 percent for some systems.

Improvements of the thermal storage could help the solar thermal power plant to become marketable, because it delivers electricity to the grid, independent of the solar cycle.
The most promising technique for an efficient storage of solar energy is the tower technology. Through higher thermal efficiency and greater progress ratios, it has a good cost reduction potential. But as table 5.8. shows, trough technology is the most used one for solar power plants.

Location	Cycle	CSP technology	Solar capacity [MW electricity]
Egypt	Combined Cycle	Investor's Choice	35
Greece	Steam Cycle	Trough	52
India	Combined Cycle	Trough	35
Iran	Combined Cycle	Trough	67
Israel	Combined Cycle	Trough	100 - 500

Table 5.8: Some current CSP projects [58]

[57] Market & Policy Trends in IEA Countries; 2004; p.88
[58] Cf. www.solarpaces.org

6. Biomass characteristics

6.1 Moisture

The moisture content of solid bio fuels can vary strongly as it depends on harvesting time, location, type and duration of storage and fuel preparation. It might range from less than 10 percent (wood processing industry by-products) up to 50 percent (freshly cut wood). The moisture content is not only relevant for the calorific value but also for the storage conditions, the combustion temperature and the amount of exhaust gas.

Two methods (dry basis and wet basis) are commonly used to specify the total moisture content. It is important to distinguish between them.

$$Moisture_{drybasis} = 100 \times \left(\frac{WetWeight - DryWeight}{DryWeight}\right) \tag{6-1}$$

$$Moisture_{wetbasis} = 100 \times \left(\frac{WetWeight - DryWeight}{WetWeight}\right) \tag{6-2}$$

Whereas dry weight refers to wood after a standardized drying process, wet weight refers to wet (freshly cut) wood. It is important to specify at which basis the moisture content for wet wood is measured. The following table will provide information about biomass including corresponding moisture, calorific value, ash specification and volatile compounds.

Type of biomass	Moisture % dry basis	Net calorific value MJ/kg	Total ash % dry basis	Volatile compounds
Sprucewood (with bark)	20-55	18.8	0.6	82.9
Beech-wood (with bark)	20-55	18.4	0.5	84.0
Poplar wood (Short rotation)	20-55	18.5	1.8	81.2
Willow wood (Short rotation)	20-55	18.4	2.0	80.3
Rye straw		17.4	4.8	76.4
Wheat straw	15	17.2	5.7	77.0
Barley straw	15-30	17.5	4.8	77.3
Corn straw	15	17.7	6.7	76.8
Wheat whole crop		17.1	4.1	77.6
Wheat grain		17.0	2.7	80.0
Sugar cane stalk (bagasse)	40-50	8.0	4.0	80

Table 6.1: Properties of biomass; abstract [24]

This table only contains some types of biomass and a detailed list is added in appendix 3.

The moisture concentration in biomass has an effect on its quality. Figure 6.1. reveals an interrelationship between lower heating value and moisture content showing that the net calorific value is decreasing from approximately 18,5 MJ/kg to zero, while the total moisture is increasing. The net calorific value is zero at a total moisture of approximately 88 percent.

Freshly harvested wood is characterized by the total moisture of about 50 – 55 percent, which results in a low heating value. Freshly cut and air-dried wood has a moisture content of 20 – 25 percent after a long period and thereby an increased net calorific value between 13 and 14 MJ/kg. This example shows how important it is to dry biomass in order to produce fuel with an increased heating value.

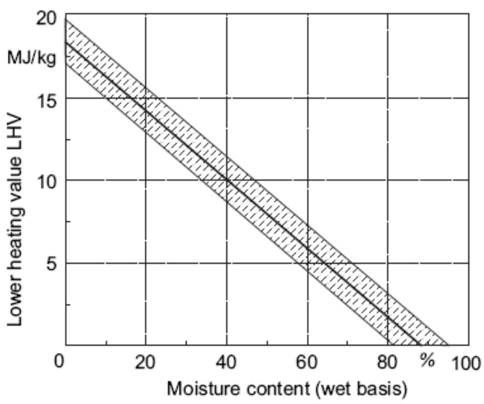


Figure 6.1: Interrelationship between moisture content and lower heating value in [MJ/kg]; sources [24]

Net calorific value or lower heating value is defined as:

$$LHV[\frac{MJ}{kg}] = 34,8 * c + 93,9 * h + 10,5 * s + 6,3 * n - 10,8 * o - 2,5 * w \qquad (6\text{-}3)$$

LHV is the amount of heat released by combusting a specified quantity (initially at 25 °C or another reference state) and returning the temperature of the combustion products to 150 °C and Lower Heating Value assumes the latent heat of vaporization of water in the reaction products is not recovered"

As mentioned before, the High Heating Value (HHV or gross calorific value) is also often used and defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, where higher heating value takes into account the latent heat of vaporization of water in the combustion products

The differences can mathematically be described as follows:

$$LHV \ [\frac{kJ}{kg}] = HHV \ [\frac{kJ}{kg}] - 20441 \ [\frac{kJ}{kg}] * u[\frac{kg}{kg}] \qquad (6\text{-}4)$$

u is described by the $Moisture_{drybasis}$ formula (6-1).

Another negative effect of an increasing moisture content is the decomposition of biomass which for wet biomass being stored outside can mean a dry mass loss up to 3 percent per month [31].
The moisture content declines stronger at the beginning period after cutting and less strong in later periods. Simsa et al. suggest "*For the all-year-round harvested system, the material will be stored as whole trees at the landing for 1 month before transporting to the power plant*" [59], which should raise the moisture content to around 40 percent.

6.2 Other characteristics

Other important characteristics of biomass are mass, volume and density as well as shape particle size and the already mentioned ash content.
Two relationships being of importance for bio energy (wood) are introduced as follows. Both mainly depend on the moisture content of biomass.

Energy = Mass x Heating value (6-5)

Mass = Volume x Density (6-6)

For some biomass types as charcoal or black liquor it is common to use the measure unit metric ton (1000 kilograms). The situation is different for round wood or fuel wood for which in the past stacked volume was used which is equal to 0,65 of solid

[59] Simsa et al.; 2004; p. 29

cubic meter. A currently used measurement unit for that kind of biomass is solid volume in cubic meter. For wood chips and pellets bulk volume units are commonly used, usually in cubic meter. The next table will show how to convert one measure unit into the other.

	mass (metric ton)	solid volume (CUM)	bulk volume (CUM)
mass (metric ton)	1	1,3 -2,5	4,9
solid volume (CUM)	0,4 - 0,75	1	2,4
bulk volume (CUM)	0,2	0,6	1

Table 6.2: Conversion factors for wood fuel units; sources [24]

This information is important in relation to transport and storage cost. In his review paper "Energy production from biomass (part 1)" Peter McKendry proposes that "*The density of the processed product impacts on fuel storage requirements, the sizing of the materials handling system and how the material is likely to behave during subsequent thermo-chemical/biological processing as a fuel/feedstock.* " [60]

In order to draw a comparison, the next table presents data on bulk volume and bulk density of woody and straw biomasses.

Biomass	Bulk volume (m3/t, daf)	Bulk density (t/m3, daf)
Wood		
Hardwood chips	4,4	0,23
Softwood chips	5,2 - 5,6	0,18 - 0,19
Pellets	1,6 - 1,8	0,56 - 0,63
Sawdust	6,2	0,12
Planer shavings	10,3	0,1
Straw		
Loose	24,7 - 49,5	0,02 - 0,04
Chopped	12 - 49,5	0,02 - 0,08
Baled	4,9 - 9	0,11
Moduled	0,8 - 10,3	0,1 - 1,25
Hammermilled	9,9 - 49,5	0,02 - 0,11
Cubed	1,5 - 3,1	0,32 - 0,67
Pelleted	1,4 - 1,8	0,56 - 0,71

Table 6.3: Bulk volume and bulk density of selected biomasses [61]

[60] Cf. McKendry; 2002; p. 44
[61] Cf. McKendry, Energy production from biomass (part 1); p. 44; daf = dry, ash free tonnes

As it is shown in table 6.3., the volume is decreasing and therefore the density of pelleted biomass is increasing. This means additional work as well as energy loss and extra costs.
Straw is a good example as it has a very low bulk density of 0,02 – 0,04 [t/m^3; daf] which causes high costs for transportation. As already mentioned, the best way to make straw more interesting for the energy sector, is to launch it in pelleted form. The same applies for wood pellets.

Particle size and shape are relevant characteristics for the transportation of bio-fuel and its handling during the process.

6.3 Wood chips

The primary factors affecting wood-fuel quality are:

- Climatic conditions
- Time of the year
- Tree species
- Part of the stem
- Storage phase

The production of consistent high-quality wood chips is directly related to the type of raw material used and maintenance of the cutting edges of the knives or screw of the chipper. The size of wood chips produced by chippers can be determined by:

- In-feed roller speed (discs and drum chippers)
- Number of knives (disc and drum chippers)
- Knife settings (disc and drum chippers)
- Pitch of screw (screw cone chippers)
- Rotational speed of disc, drum or screw

The density of wood chips is too low for a long-distance transport and can only be seen as intermediate product before pelletising or thermal/chemical conversion.

Name	Hole size in mm	Fine	Medium	Coarse	Air spout	Gassifier
Dust	3,15	< 10 %	< 8%	< 8%	>2%	<4%
Small	3,15 - 8	<35%	<30%	<20	>5%	<8%
Medium	8 - 16	*	*	*	>60%**	<25%
Large	16 - 45	<60%	*	*	>60%**	>60%***
Extra Large	45 - 63	<2,5%	<6%	*	<15%	>60%***
Overlarge	>63	<0,25%	<0,6%	<3%	<3%	>60%***
Overlong 10	100 - 200	<1,5%	<3%	<6%	<4,5%	<6%
Overlong 20	> 200	0%	<0,5%	<1,5%	<0,8	<1,5%

Table 6.4: Wood chips classification [62]

The description of the usage of these different wood chips sizes is quoted as follows:

The first type fine is in use for small domestic boilers where a silo system and a screw conveyor supply the boiler. In this system the screw is too sensitive for coarse chips, therefore these chips are more suitable for large boilers with a stronger constructed screw.
For heating plants, where chips are normally forced into the boiler, extra coarse chips are most suitable, the fine-material content of which should be low.
"*Air spout chips are suitable for installations throwing the chips into the combustion chamber*" [63]
The last type of chips namely gasifiers is suitable for small gasification plants which should have a very small amount of dust [15].

If storage of wood chips is necessary, it is recommended to do so under the roof. Some experiments have shown that after 4-6 months, the moisture content drops from approximately 45 percent to 25-30 percent, whereas without an ideal storage the moisture content stays the same or even increases [15].

[62] Cf. Serup et al.; Wood for Energy Production Technology - Environment – Economy; 2002
* No demands
** These two classes shall make up for a minimum of 60 %
*** These three classes shall make up for a minimum of 60 %
**** Particles with the following dimensions are not allowed
- longer than 500 mm with a diameter >10 mm
- larger than 30 x 50 x 200 mm

[63] Serup et al.; Wood for Energy Production Technology - Environment – Economy; 2002; p.14

7. Drying process for wood chips

7.1 In general

Why is it useful to dry wood chips and thus cause additional energy costs (if air drying is not taking place)?

One of the most important advantages will be presented in the figure below, showing the mass reduction and energy increase achievable with thermal drying process.

"(…) *drying reduces mass by up to about 50% yielding an energy increase of more than 20%. Thus the effects on the overall power plant efficiency can be significant* (…)" [64].

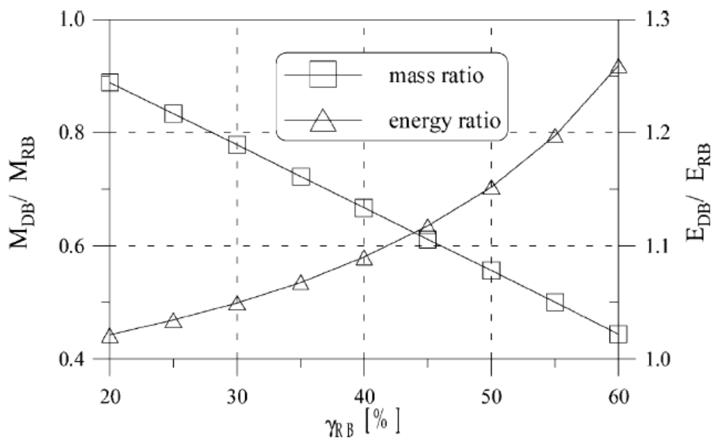


Figure 7.1: Mass reduction and energy increase achievable with thermal drying process [64].

As mentioned in the last chapter, air-dry storage is sufficient for domestic use, but for industrial needs the process of thermal drying usually takes place directly before wood chips are conveyed to the conversion facility. This requires dryer systems which have to deal with a high mass-output. Mass reduction and energy increase are not the only reason for drying. Some conversion processes such as gasification need wood fuel with a low moisture content for an ideal working basis. The main parameters controlling drying are: temperature and pressure of the drying medium, slip velocity and humidity, if the drying medium is air.

[64] Carapellucci; 2002; p. 151

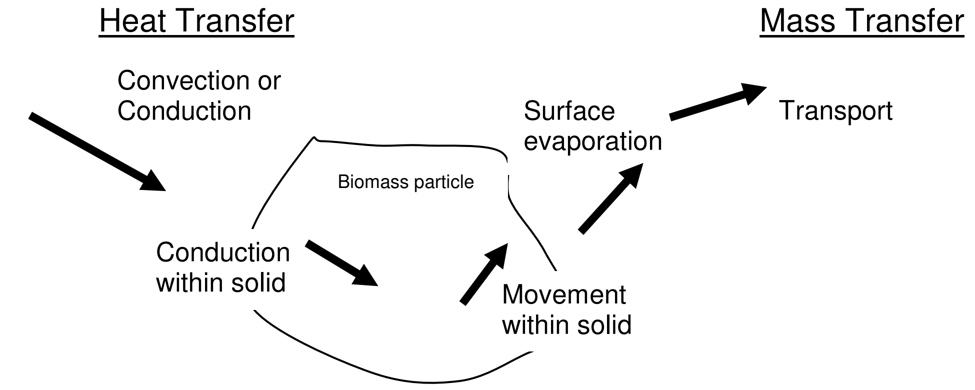


Figure 7.2: Heat and Mass transfers by drying process

Figure 7.2 shows interacting heat and mass transfer in the drying process.
In the figure below, temperature characteristics and the connected drying rate curve of material are plotted against time, showing an ideal progress of drying periods.

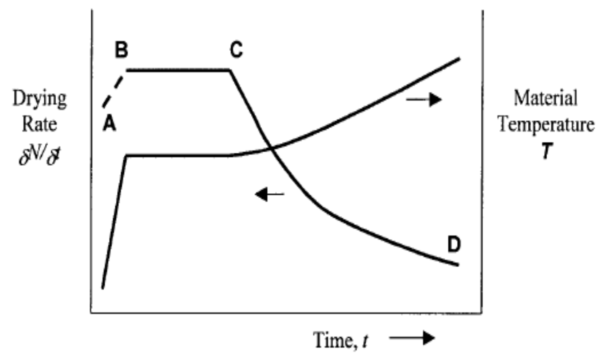


Figure 7.3: Periods of temperature and drying rate of biomass material against time [38]

As shown in figure 7.3, the drying line is divided into three periods with different drying velocities. In the first line from A to B, the material is heated up very quickly and the drying rate increases, too. The following period B - C describes a constant drying period and constant temperature although heat is still supplied. At this stage the "…*movement of water through the solid is sufficiently rapid to maintain saturated conditions at the surface, and evaporation is equivalent to that from a body of water*." [65]

The decreasing drying rate in period C – D is caused by the insufficient internal supply of water to the material surface. "*This period is often divided into two, a period*

[65] Brammer & Bridgwater; 1999; p. 249

where the material surface is partially wet and neither mechanism dominates fully, followed by a period where the material surface is completely dry and movement of water through the solid is fully rate limiting" [66]. At this stage, the surface of wood chips enters the hygroscopic range. At the same time the surface temperature starts to rise to that of the drying medium.

In order to achieve low-moisture material, a stronger input of heat is necessary and consequently the drying time extends.

In their paper Johansson et al. investigated on high temperature drying of single wood chips particles with hot air and superheated steam. They indicated the behaviour of wood chips particles during the drying on a graph. A comparison of the temperature run, the drying rate curve of theoretical ideal curves from figure 7.3 and of practical results of work [39], show strong similarities.
Model of wood chips drying in superheated steam:

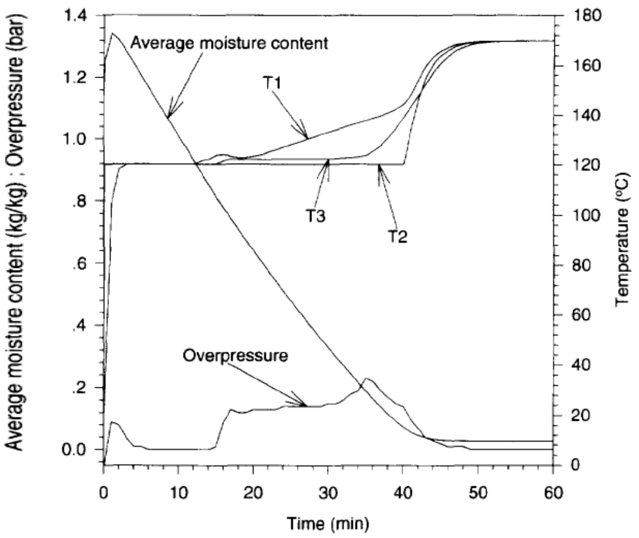


Figure 7.4: Behaviour of wood chips drying in superheated steam [66]

The drying time is influenced also by the size of the particles or the biomass type, and the total drying time is not as sensitive to the wood chip length as to the thickness. The reduction in the direction with the highest resistance flow is the most effective way of shortening the drying time.

Length (mm)	Thickness (mm)	Total drying time (s)
50	7	2880
50	14	6060
50	3,5	1440
100	7	3840
25	7	2280

Table 7.1: The influence of chip geometry on drying [66]

The results of table 7.1 show that thickness has a stronger influence on the drying time than on the length. Double thickness also means double drying time, while if the length is doubled, time increases less. Different biomass types have a variable permeability which causes a positive or negative effect on the drying forces. For example "*The total drying time is about 5 % shorter for pine wood* (…) " than for spruce wood and "(…) *the period of constant drying rate is longer for pine due to its higher permeability which allows the capillary forces to keep the surface above fibre saturation point (FSP) for longer time.*" [67]

In the last phase of drying the temperature of wood can reach a critical value which causes thermal degradation and increases organic emission. Up to a temperature of ~ 100 °C for wood chips, both effects are minimal.

The first noticeable degradation starts at temperatures between 100 and 150 °C. With an increasing temperature also the degradation is rising and up to around 200 °C wood thermal degradation is reported to occur mainly on the outer surface of wood [41].
Organic emissions also strongly depend on the temperature in the thermal drying process. Emissions can result in strong smell or even ozone formations which might cause problems if hot air is used for drying. If superheated steam is used the organically loaded condensed water flows will cause problems and also additional costs for a sewage plant [41].

[66] Drying at 2 bar; 170°C; cf. Christian Fyhr & Anders Rasmuson; p.2832
[67] Cf. Fyhr/Rasmuson; 1997; p. 2828

How fast the emission of organic elements will rise if the temperature increases, will be shown in table 7.2.

Temperature range [°C]	Emission [g organics/kg dry solids]
150 - 200	~1
250 - 300	~40
300 - 350	~110

Table 7.2: Amounts of organic emissions released from pine bark drying with short delay times in a laboratory-scale steam dryer [68]

In order to avoid problems such as exhaust cleaning or sewage treatment if air is used as drying medium, (Jukka-Pekka Spets and Pekka Ahtila) suggest using a multi-stage system instead of a single stage dryer system. The multi stage system heats the same dry-airflow several times with always higher moisture content and uses it again for drying without exceeding problematic temperature.

Low drying temperature causes less problems with exhaust or waste water, but it extends the drying time and thus the costs.
Why should superheated steam be used for drying if high temperatures cause more problems?
The advantages are that the total energy efficiency is increasing because of reuse of the latent heat of evaporation, no risk of explosions (dust) and hazards and the simpler way to control it.

7.2 Heat transfer

The energy required for the evaporation can be supplied to the material in different ways: as conduction, convection, radiation and microwaves. The calculation for External -, Internal heat transfer, and External -, Internal mass transfer are based on the information provided by the following papers: Anders Johansson et al; Christian Fyhr & Anders Rasmuson. A general overview shall be given.

[68] Cf. Jukka-Pekka Spets/Pekka Ahtila; 2003; p. 7

7.2.1 External heat transfer

From the drying medium to the surface of wood chip particles heat is transported through convection. A sharp plate with laminar boundary layer is described as follows

$$Nu_x = \frac{h \times x}{k} = 0{,}332 \times \mathrm{Re}_x^{1/2} \times \mathrm{Pr}^{1/3} \qquad (7\text{-}1)$$

The particle size is defined and the flow is parallel to the large side of it. The flow hits the particle on the front side and impinges the end sides, which results in small vortices. The heat flux to the surface due to convection is:

$$q_{boundary} = h(T_\alpha - T_s) \qquad (7\text{-}2)$$

Additionally to convection, also heat is transported through radiation. This is modelled according to the Stefan-Boltzmann law with the emissivity for wood being equal to 0,9. [39]

7.2.2 Internal heat transfer

Different mechanisms are responsible for heat transport inside the material. The Fourier's law models the transport by conduction:

$$q = -\lambda \times \nabla T \qquad (7\text{-}3)$$

with an effective thermal conductivity coefficient λ accounting for heat conduction in all the three phases.

for X ≥ 0,4:

$$\lambda_T = (\frac{0{,}65}{100 \times X} + 0{,}0932) \times (1 + 3{,}65 \times 10^{-3} \times T)(0{,}986 + 2{,}695 \times X) \qquad (7\text{-}4)$$

for X ≤ 0,4:

$$\lambda_T = (0{,}129 - 0{,}049X) \times (1 + (2{,}05 + 4 \times X) \times 10^{-3} \times T)(0{,}986 + 2{,}695 \times X) \quad (7\text{-}5)$$

$$\lambda_L = 2{,}5 \times \lambda_T \qquad \text{(T in °C)} \qquad (7\text{-}6)$$

At which X is the moisture content in [kg water/kg dry wood^{-1}].
Through simultaneous transfer of mass and heat, the heat is transported by convection. This kind of heat transfer is modelled by weighing the mass fluxes of component κ with the enthalpies as:

$$q = \sum_{\substack{\alpha = l,g \\ \kappa = a,w}} \dot{m}_\alpha^\kappa \times h_\alpha^\kappa \qquad \text{where } \alpha \text{ is the phase [39]} \qquad (7\text{-}7)$$

Thus the full internal heat transfer is:

$$q = \sum_{\alpha = l,g} \dot{m}_\alpha \times h_\alpha - \lambda \times \nabla T \qquad (7\text{-}8)$$

7.3 Mass transfer

7.3.1 External mass transfer

By using air as a drying medium, the convective flux of vapour across the boundary is:

$$\dot{m}_{g,boundary} = k \times M_w \times \frac{p}{RT} \times (y_g^{(w,s)} - y_g^{(w,\varpi)}) \qquad (7\text{-}9)$$

"*In case of pure superheated steam at the drying medium, there is no convective transport of vapour due to concentration gradients from the surface of the particle to the surrounding.*" [69]

[69] Johansson et al; 1997; p. 2845

7.3.2 Internal mass transfer

The internal mass transfer (fluids) can proceed in two different ways:

a) "(…) *gas and liquid inside the material is transported by convection through the interconnected voids of the wood structure due to a gradient of the pressure within each phase"* [70] and

b) "(…) *moisture also migrates via a diffusional mechanism, of which there are two different types. The bound water migrates through the cell-wall matrix, which is present for moisture contents below the fibre saturation point."* [70]
The other diffusion mechanism is the intergas diffusion of vapour.

a) Darcy's law is used for modelling this kind of flow of gas and liquid:

$$\dot{m}_\alpha = -\rho_\alpha \times K_{sat} \times \frac{k_\alpha}{\mu_\alpha} \times (\nabla p_\alpha - \rho_\alpha \times g) \qquad (7\text{-}10)$$

k_α is the relative permeability which is zero at the fibre saturation point and therefore there is no flux of free liquid. This factor is positive for the gaseous phase as well as for nearly full saturation. Each phase is related to another via the capillary pressure:

$$p_c = p_g - p_l \qquad (7\text{-}11)$$

b) Through diffusion mechanism, the bound water migrates through the cell-wall matrix, "(…) *which is present for moisture contents below the fibre saturation point, is treated as a diffusion process with the moisture content as the driving force."* [70]:

$$\dot{m}_l^{(w)} = -F_{th} \nabla X \qquad \text{with the units [kg*m}^{-1}\text{*s}^{-1}] \qquad (7\text{-}12)$$

[70] Cf. Johansson et al; 1997; p. 2846

If air is used or presented as drying medium the intergas diffusion of vapour is another diffusion mechanism.

$$\dot{m}_g^{(w)} = -F_{eff} \nabla \rho_g^{(w)} \tag{7-13}$$

where D_{eff} is the effective diffusion coefficient accounting for the liquid saturation and the tortuosity of the pores [39].

7.4 Balance and Boundary equation

The mass balance for each component κ (water and air) is:

$$\frac{\partial M^{\mathrm{K}}}{\partial t} = \nabla \times \left(\sum_{\alpha = l,g} \dot{m}_\alpha{}^{(\mathrm{K})} \right) \tag{7-14}$$

For moisture contents below the fibre saturation point, the water is treated as bound water.
The energy balance is:

$$\frac{\partial H}{\partial t} = \nabla \times \sum q \tag{7-15}$$

Boundary:

The total pressure at the boundaries, by setting very high permeabilities at the surface, is equal to the pressure of the drying medium.

$$p_g = p_\alpha \tag{7-16}$$

In the case of air being the surrounding medium, the additional mass transfer condition is:

$$\dot{m}_{g,surface} = k \times M_w \times \frac{p}{RT} \times (y_g^{(w,s)} - y_g^{(w,\varpi)}) \tag{7-17}$$

and for heat:

$$q_{boundary} = h \times (T_{\alpha} - T_s) + \sigma \times \varepsilon \times (T_{\varpi}^4 - T_s^4) + \sum \dot{m}_g \times h_g \qquad (7\text{-}18)$$

where the emissivity, ε, is set to 0,9.

For proper descriptions of mass and heat transfers in wood-chips drying, see Anders Johansson et al; Christian Fyhr & Anders Rasmuson.

8. Dryer classification

The biomass energy plant should run continuously in order to achieve its highest capacity. Thus, the delivery of biomass to the combustion/conversion reactor must happen continuously. This situation requires continuous drying, which has the disadvantage of being expensive and consume a lot of space. Batch dryers are usually cheaper and smaller, this is why they are used for small plants which only have limited capacities.
The summarisation of dryer classification is based on J.G. Brammer's and A.V. Bridgwater's paper "Drying technologies for an integrated gasification bio-energy plant".

8.1 Based on heat/mass transfer

8.1.1 Convective

The medium which is used for drying biomass is gaseous. Heated air, combustion products or superheated steam can be such a medium. Some dryer facilities use a mixture of heated air and combustion exhaust, but the source of heat is always the gaseous drying medium.
The following table will provide an overview of the classification of convective batch and continuous dryer.

<table>
<tr><td rowspan="13">Mode of Operation</td><td colspan="2">Convective</td></tr>
<tr><td rowspan="2">batch</td><td>Fluidised bed</td></tr>
<tr><td>Perforated tray drying room</td></tr>
<tr><td rowspan="10">continuous</td><td>Rotating shelf</td></tr>
<tr><td>Perforated band</td></tr>
<tr><td>Moving bed</td></tr>
<tr><td>Tunnel</td></tr>
<tr><td>Rotary-louvre</td></tr>
<tr><td>Fluidised bed</td></tr>
<tr><td>Cascading rotary</td></tr>
<tr><td>Pneumatic conveying</td></tr>
<tr><td>Spouted bed</td></tr>
<tr><td>Spray</td></tr>
</table>

Table 8.1: Classification of batch and continuous convective dryer

The vast majority of dryers which are suitable for biomass drying are convective and continuous. Some of the above mentioned dryers will briefly be described below.

Batch:

- Perforated tray drying room/Fluidised bed

The advantages of such dryers are: low capital costs, good heat, efficient mass transfer and the minimal disturbance of the material being dried. Air is usually the drying medium and flows through the perforated floor and then through biomass which lies on this floor [38].

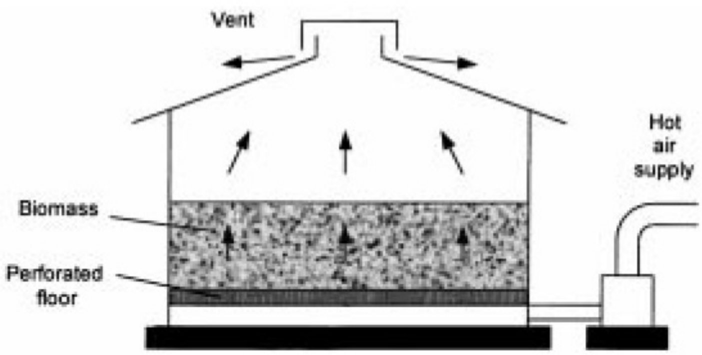


Figure 8.1: Perforated floor bin dryer [71]

The depth of the bed being chosen is connected to the characteristics of biomass and the desired drying characteristics. This kind of dryer is often used in agricultural industry.

The top bin dryer works similarly. Here the perforated floor is located near the roof. "*Once dry, this material is allowed to fall through doors in the perforated floor into the lower, much larger region of the bin which acts as a store*." [71]

It is possible to automate both drying systems for material loading and unloading. According to the degrees of automation and system size the capital expenditure grows. Only the poor flow properties of most biomass fuel could limit the usage of such systems [38].

[71] Cf. Brammer/Bridgwater; 1999; pp. 169-273

Continuous:

- Perforated band

"(…) *widely used is the band or belt dryer, in which the drying medium is blown through a thin static layer of material on a moving band.*" These "(…) *continuous through-circulation dryer are most often used for materials that required gentle handling.*" [71]
Drying media, which are mostly air or combustion products, flow through the thin layer of the wet products, optionally upwards or downwards.
Figure 8.2 illustrates a single stage perforated band dryer.

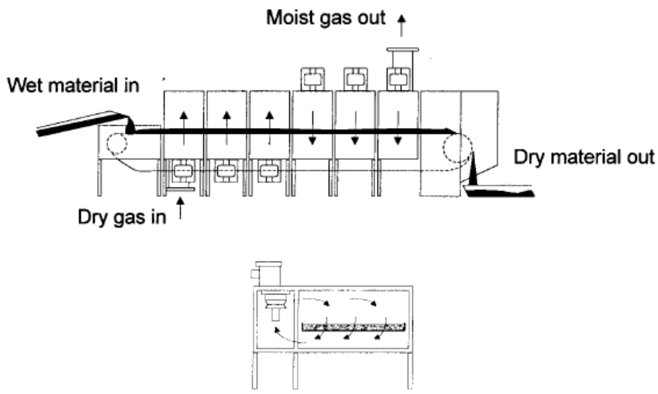


Figure 8.2: Single stage perforated band dryer [71]

The same system can be applied for the multi-stage multi-pass band dryer. In this case at the end of the first band dryer material is discharged onto the beginning of the next one. Thus, it is possible to generated a new drying surface and set up new parameters for the drying medium.
A multi-stage multi-pass band dryer also has a number of bands. In this case the bands are arranged one above the other, but are working like the multi-pass band dryer where material flows from one onto the next band. The same re-exposure benefit is gained, but dryer length is much reduced at the expense of height [38].

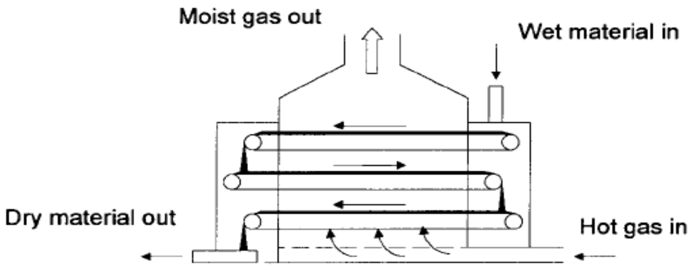


Figure 8.3: Multi-stage multi-pass perforated band dryer [71]

- Pneumatic conveying

Flash dryers use a high velocity gas flow to dry wet material rapidly with short residence time. This dryer is perfectly suitable for drying small particles which are much smaller than wood chips used for the gasification process.

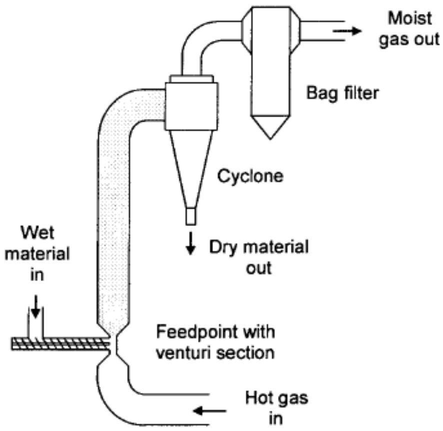


Figure 8.4: Flash dryer

There are attempts to develop flash dryers for biomass wood-chips up to a size of 50 mm.

A further development of this kind of dryer is the pneumatic conveying pressurised steam dryer which uses only indirectly heated steam from the liberated moisture as the conveying and drying medium. A couple of years ago this system was developed in Sweden in cooperation of some companies [38].

- Spray dryers

Spray dryers are not applicable for biomass such as wood or particles with this typical size. This type of dryer is used in pharmacy and food industry and suits large capacities of products which are powdery, spherical and freely flowing after drying.

8.1.2 Contact

There are some reasons why the application of a contact dryer could be preferred:

- "(…) *the material being dried cannot be exposed to combustion products*
- *direct heating will lead to excessive entrainment and carry-over of fines or dust*;
- *a low-cost source of low to medium pressure steam is available.* " [72]

Contact dryers are also used for processes that require an extreme control of the dryer exhaust. Only the continuous indirect (=contact) dryer is used for biomass. The dryers listed in the table below are only seldom used for this kind of application.

	Contact	
Mode of Operation	batch	Tray/Oven
		Double cone
		Conical, Vertical pan
		Horizontal agitated Filter-dryer
	continuous	Plate
		Belt/band
		indirect rotary
		Horizontal agitated thin film drum cylinder

Table 8.2: Classification for batch and continuous contact dryer

[72] Cf. Brammer/Bridgwater; 1999; p. 278

8.1.3 Other types of dryers

These types of dryers are rarely applied in order to dry biomass at large scale. Solar technology is used to dry fruits and vegetables and could also be used for small size power plants. It is an opportunity to dry materials at a low price because of the simple technology and low running costs. M. Reuss et al. described an experimental investigation on a solar pilot plant for wood drying.

Mode of Operation	batch	Freeze
		RF/Microwave
		Solar
	continuous	IR tunnel
		RF/Microwave
		Solar

Table 8.3: Classification for batch and continuous contact dryer

Some companies offer solar dryers for Sewage Sludge, which is used as biomass after drying.

8.2 Based on geometry/configuration

In some cases a contributing factor for selecting a dryer system is the available area for this application. The configuration in geometry of dryer systems can be classified as follows:

Geometry	Through-circulation	Batch perforated floor in bin or silo
		Continuous band
	Rotary	Louver
		Cascade
		Steam tube
	Fluid bed	Conventional once-through
		Pressurised recycled steam
	Pneumatic conveying	Pressurised recycled steam

Table 8.4: Dryer classification based on geometry

Already described systems are the Batch perforated floor in bin or silo, continuous band and Pneumatic conveying drying system. In the next chapter Rotary and Fluid drying systems will be discussed. Both types are normally used to dry wet wood-chips.

9. Suitable dryers for gasification

9.1 Rotary drum

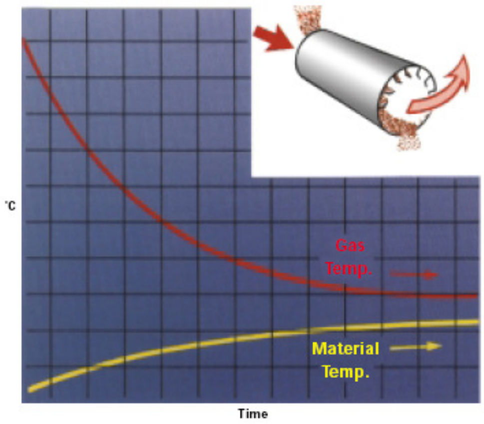
The rotary drum is probably the most frequently used type of dryer for biomass power plants. There are two operating methods for rotary drums: the parallel-flow principle and the counter-flow principle. Each of these principles has advantages which have to be considered in the construction.

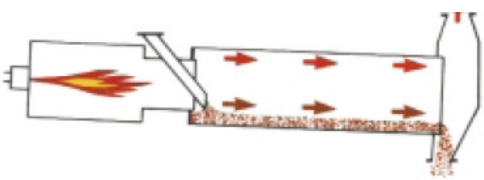
- Parallel flow

Parallel-flow principle dryers are the most widely used and are particularly suitable for drying materials containing a high moisture content and that is heat sensitive or tends to stick or cake.

The wet material gets in contact with the gas at its highest temperature, which rapidly evaporates surface moisture. The initial heat-transfer rate is high, causing an immediate and considerable drop of gas temperature preventing an overheating of the material and the dryer shell.

"*The final product is in contact with gas at its lowest temperature, enabling the moisture content to be readily controlled, usually by maintaining the dryer exhaust gas temperature at a pre-set value.*" [73]





a) b)

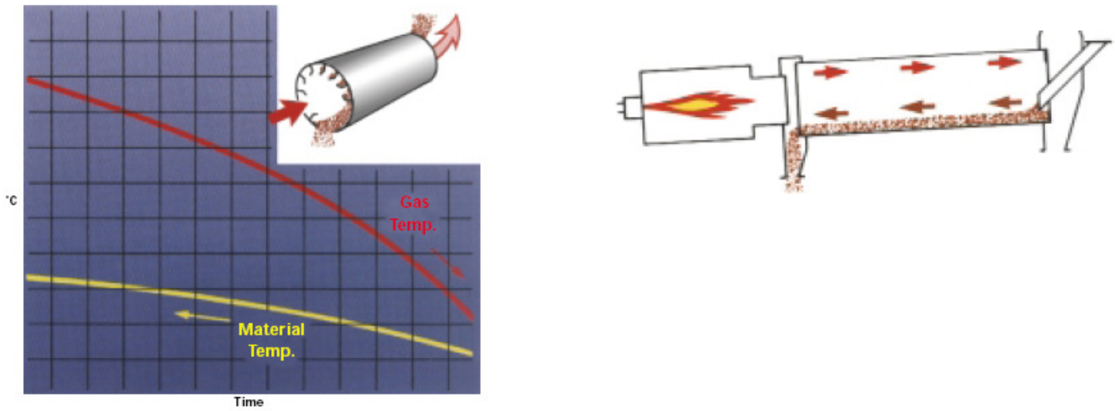
Figure 9.1: a) Parallel-Flow Principle with temperatures characteristics, b) with gas or oil burner to achieve the necessary temperature

[73] Source: Information material from www.barr-rosin.com for Rotary dryers

- Counter flow

Counter-flow principle dryers are more suitable for materials that must be dried to very low levels of moisture, where the last traces of moisture are difficult to remove, or where an elevated product-temperature is desirable.

However, since the final product is in contact with the gas at its highest temperature, the counter-flow dryer is often unsuitable for heat-sensitive materials [46].



a) b)

Figure 9.2: a) Counter Flow Principle with temperatures characteristics, b) with gas or oil burner to achieve the necessary temperature

If the drying medium is pure vapour, it has to be superheated in order to avoid a recondensation during the drying process [38].

- Rotary louver dryer

Due to the complexity of construction, the acquisition costs for rotary louver dryers are high, but they approve a very efficient heat transfer with less substantial volumes compared to rotary dryers. Air or combustion products are used as a drying medium.

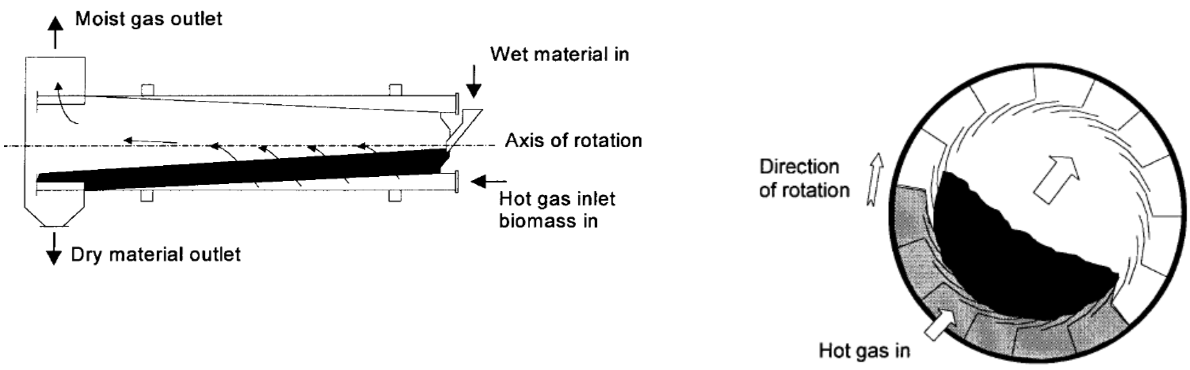


Figure 9.3: Rotary louver dryer [74]

The drying conditions are gentler as in rotary cascade dryers because the material is constantly rolling in the bed. Thus, it is best suitable for freely flowing materials. By the utilisation of multiple gas feeds, the temperature can be controlled along the dryer.

- Rotary cascade dryer

This type of dryer is commonly used for many applications in the industry. A lot of experience has been collected and therefore the rotary cascade dryer is perceived to be a low-risk choice.

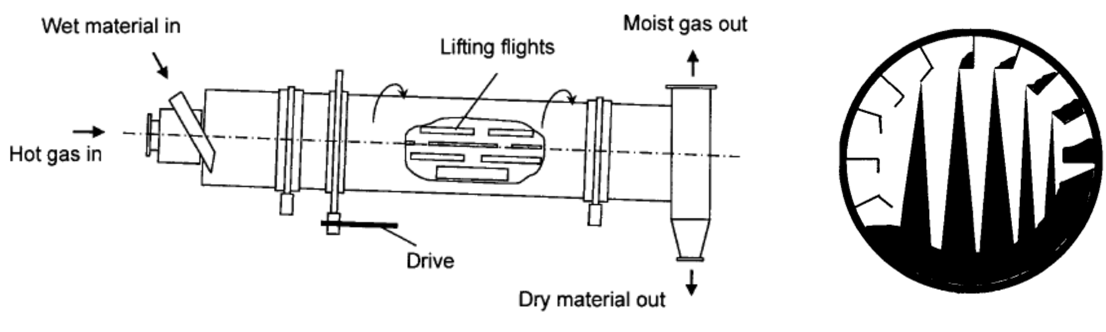


Figure 9.4: Rotary cascade dryer [74]

"The length to diameter ratio of shell usually lies between 4 and 10, with actual diameter ranging from <1 m to >6 m depending on throughput." [75] In both parallel-

[74] Cf. Brammer, Bridgwater; 1999; pp. 275
[75] Cf. Brammer, Bridgwater; 1999; pp. 276-277

flow and counter-flow systems air, combustion products and superheated steam can be used as drying medium.
In order to intensify the drying process or easily design the dryer, it is possible to equip the dryer with gas burner or an oil burner to achieve the necessary temperature.

The period in which material is falling through the gas stream is the most important one, because in this moment the drying process is taking place. The most used system is the counter-flow and thus the dried material encounters the gas at its highest temperature. This is not suitable for all biomass products, as it was already mentioned beforehand [38].
Forces which are responsible for the transport of the material inside the dryer are a combination of gravity and in the case of parallel-flow dryers entrainment with the drying medium. In order to keep the operation risk as low as possible, the inlet temperature is often limited to about 250°C.

"*Residence time in the dryer is controlled by a number of factors including flight design (the amount of hold-up on the flight), number of flights, rotational speed, gas velocity, dryer length and dryer inclination.*" [75]

- The indirect rotary dryer or steam cube dryer

This type of dryer is suitable when steam is available. The advantage of the reduced exhaust gas-flow and carry-over make an indirect rotary option attractive [38].

A typical application of such dryers suits for products with a small particle size, where dust generation could cause problems. This system secures that the dryer exhaust can exactly be controlled.

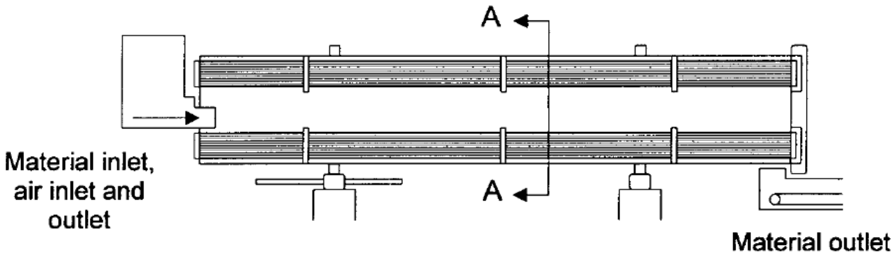
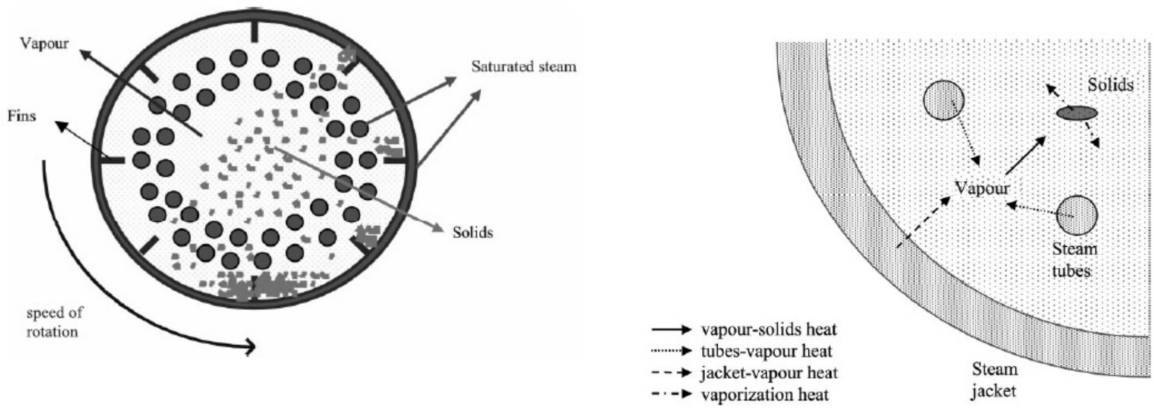


Figure 9.5: The indirect rotary dryer or steam cube dryer [75]

“The tubes are fixed to the dryer end plates and rotate with it. The dryer shell is usually inclined at a small angle to the horizontal, and the wet material enters the shell at one end and moves down the dryer by gravity, assisted by the ploughing effect as the tubes rotate through the material bed.” [76]



a) b)

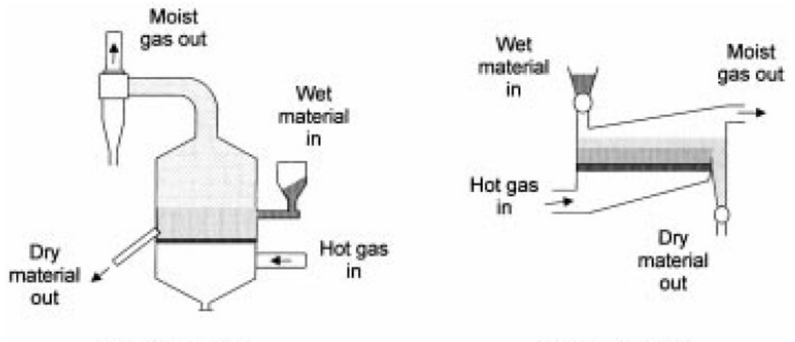
Figure 9.6: a) Cross section of indirect rotary dryer, b) Mass and Heat flows inside of indirect rotary dryer

The heat transfer happens through conduction from the dryer surface whose temperature is close to steam temperature.

9.2 Fluidized bed dryer

The advantages of the fluidized bed dryer are its high heat transfer and a very good mixture of materials. Therefore, this type of dryer is often considered to provide ideal drying [38].
It can be designed as batch or continuous working process dryer.

[76] Cf. Brammer, Bridgwater; 1999; p. 278-279



a) b)

Figure 9.7: Two configurations of fluidized bed dryers [77]

For continuous processes, beds are usually either the well-mixed type (a) or the plug-flow type (b).

In order to apply fluid bed dryers, the choice of material is an important consideration. The material must have a uniform size-distribution, a small size and it must be suitable for fluidisation.

If the particle size is bigger, the drying medium velocity is higher in order to achieve the fluidisation, thus the risk of higher entrainment of smaller particles rises significantly. In order to prevent dust exhaust problems, a cyclone separation is nearly always joined after drying [38].

- Pressurised steam fluid dryer

The first application of this type of dryer was used for brewing, food and sugar processing industries and not in wood chips drying. At the moment "(…) *two systems are in operation for the drying of wood chips with a mean particle size of up to 50 mm.*" [77]

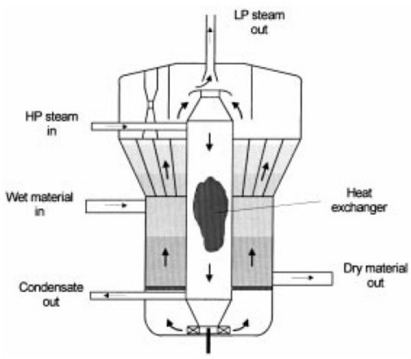


Figure 9.8: Pressurised steam fluid dryer [38]

[77] Cf. Brammer, Bridgwater; 1999; pp. 280-282

Through their complexity of design the capital costs are high and "(…) *the dryer is likely only to prove attractive for relatively large scale plant and where the full benefit of energy recovery can be realised.*" [77]

10. Simplified mathematic model

The simplifications for this model are:

- Steam pressure is constantly at 1 bar
- Steam is supposed to be an ideal gas
- Drying rate over the dryer length is constant
- Furthermore, some parameters have been decided freely

Superheated Steam:

For some reason, the inlet temperature of superheated steam should stay below the boundary of 250 °C [38].

Inlet temperature of the steam: $T_{s,in}$ = 225 +273,15 K
Outlet temperature of the steam: $T_{s,out}$ = 125 +273,15 K

The outlet temperature should not fall below the curve of vaporisation in order to avoid condensation which would occur at a pressure of 1 bar at 100°C.

With the corresponding

specific enthalpy [48]: $h_{s,in}$ = 2924 kJ/kg
$h_{s,out}$ = 2726 kJ/kg

For superheated steam the amount of energy which can be delivered is:

$$\Delta h_{s,ex} = h_{s,in} - h_{s,out} \qquad (10\text{-}1)$$

over the length of the dryer.
density: $\rho_{s,in}$ = 0,4368 kg/m³
$\rho_{s,out}$ = 0,5503 kg/m³.

The maximum velocity of superheated steam can be calculated through the forces which work on every wood chip during the drying time. Referring to the information from [38, 44] the following velocities for superheated steam can be chosen:

$V_{s,1} = 2$ m/s
$V_{s,2} = 3$ m/s
$V_{s,3} = 4$ m/s
$V_{s,4} = 5$ m/s
$V_{s,5} = 7$ m/s
$V_{s,6} = 8$ m/s

Biomass:

Inlet moisture: $X_{b,in} = 50$ %
Outlet moisture: $X_{b,out} = 15$ %

The temperature of Biomass is equal to the surrounding air temperature:

$T_{b,in} = 25 + 273{,}15$ K

Water balance

With the help of water balance it is possible to calculate how much water ($\dot{m}_{,w,ab}$) must be removed from biomass ($\dot{m}_{,b,in}$) in order to receive the desired amount of biomass ($\dot{m}_{,b,out}$) at the end of the drying process.

$$\dot{m}_{,b,dry} = \dot{m}_{b,out} * (1-X_{,b,out}) = \dot{m}_{b,in} * (1-X_{,b,in}) \quad (10\text{-}2)$$

$$\dot{m}_{b,in} = \frac{\dot{m}_{,b,dry}}{1-X_{b,in}} \quad (10\text{-}3)$$

$$\dot{m}_{,w,ab} = \dot{m}_{b,in} - \dot{m}_{b,out} \quad (10\text{-}4)$$

Energy balance

The energy balance, the information on the amount of water and the maximum amount of energy which is supplied by the gas (superheated steam), make an estimation of the total required heat possible.

Energy for heating biomass:

$$Q_{bio} = \dot{m}_{bio} * c_{p,bio} * (T_{b,out} - T_{b,in}) \qquad (10\text{-}5)$$

and for the rest of the water:

$$Q_{w,rest} = \dot{m}_{w,rest} * c_{p,w} * (T_{w,out} - T_{w,in}) \qquad (10\text{-}6)$$

In both cases the inside and outside temperature of wood and water are equal. In this case, it makes more sense to bring this two terms together. In order to do so a calculation of the specific heat capacity of wet wood is required.
According to [Kollmann; 1951], the specific heat capacity for dry wood, in dependence of the temperature, can be calculated as follows:

$$C_{p,wood,dry} = 1{,}111368 + 0{,}0048567 * (T - 273{,}15) \qquad (10\text{-}7)$$

and the specific heat capacity of water (25°C) is known as

$c_{p,w}$= 4,183 kJ/kgK.

Consequently, the specific heat capacity for wet wood depending on the moisture content is:

$$\bar{c}_{p,bio} = X * c_{p,w} + (1 - X) * C_{p,wood,dry} \qquad (10\text{-}8)$$

Thus, the needed energy for $\dot{m}_{b,out}$ is:

$$Q_{b,heatup} = \dot{m}_{b,out} * \bar{c}_{p,bio} * (T_{b,max,out,p} - T_{b,in}) \qquad (10\text{-}9)$$

The water ($\dot{m}_{,w,ab}$) has to be removed through evaporation, meaning to turn water from liquid phase into gas phase and then to heat up the gas starting at boiling temperature (1 bar, ~100℃) heating up to the end-temperature of superheated steam ($T_{s,out}$).

$$Q_{evapo} = \dot{m}_{,w,ab} * (h_v + h_{gas}) \qquad (10\text{-}10)$$

h_v [kJ/kg] … specific enthalpy which is necessary to turn water from liquid phase to gas phase and

h_{gas} [kJ/kg] …specific enthalpy to turn steam from 100℃ to the initial temperature of gas

The heat losses as well as the reserve are evaluated with 5 percent

$$Q_{loss} = 0{,}05*(Q_{b,heatup}+ Q_{evapo}) \qquad (10\text{-}11)$$

$$Q_{reserv} = 0{,}05*(Q_{b,heatup}+ Q_{evapo}) \qquad (10\text{-}12)$$

The cumulative sum of the required heat is:

$$Q_{sum} = Q_{b,heatup} + Q_{evapo} + Q_{loss} + Q_{reserv} \qquad (10\text{-}13)$$

Evaporating water is a very consumptive process and therefore Q_{evapo} is the biggest part of it and requires more than 80 percent of the whole energy.
The amount of energy which is necessary to cover it, will only result from superheated steam and this means that Q_{sum} is equal to $Q_{in,steam}$.

$$Q_{sum}= Q_{in,steam} \qquad (10\text{-}14)$$

$$Q_{in,steam}= \dot{m}_{steam} * \Delta h_{s,ex} \qquad (10\text{-}15)$$

$$\dot{m}_{steam} = \frac{\dot{Q}_{sum}}{\Delta h_{s,ex}}$$

Dryer design

Information about the volumetric load and the length to diameter ration are given in chapter 12.1. For further calculation, the biomass volumetric load of the dryer (τ_{bio}) is 10 percent.

In order to make a compromise, the length-diameter ratio for parallel flow is:

$$\frac{L}{D} = 7 \Rightarrow L = 7 * D \tag{10-16}$$

Furthermore, there is a connection between steam velocity (v_s), mass flow of steam ($\dot{m}_{steam}$), density of steam (ρ_s) and the area (A_{dryer}) of the dryer.

$$v_s = \frac{\dot{m}_{steam}}{\rho_s \times A_{dryer}} \tag{10-17}$$

Where A_{dryer} is the free flow area, the area for biomass is subtracted.

$$v_s = \frac{4 \times \dot{m}_{steam}}{\rho_s \times (D \times 0{,}9)^2 \times \pi} \tag{10-18}$$

Therefore, the diameter is:

$$D = \frac{\sqrt{\frac{4 \times \dot{m}_{steam}}{\rho_s \times \pi \times v_s}}}{0{,}9} \tag{10-19}$$

Knowing about the volume of the dryer, the residence time of biomass or steam inside the dryer drum can be calculated as follows:

$$V_{dryer} = \frac{\dot{m}_{bio} \times t_{bio}}{\rho_{bio} \times \tau_{bio}} = \frac{\dot{m}_{steam} \times t_{steam}}{\rho_{steam} \times \tau_{steam}} \tag{10-20}$$

=> $$t_{bio} = \frac{\rho_{bio} \times V_{dryer} \times \tau_{bio}}{\dot{m}_{bio}}$$

Counter-flow dryers

It is difficult to estimate the initial temperature of biomass ($T_{b,max,out}$) in a dryer operating with counter flows. In case of concurrent flow it is easier because the initial temperature of biomass ($T_{b,max,out}$) will be very close to the initial temperature of gas ($T_{s,out}$) and with an increasing length of the dryer (L) probability also more correct.

The surface temperature of wood chips will keep constant at around 100℃ for a long time. When the moisture content of wood falls under 20 – 25 percent, the temperature increases and this is just shortly before biomass leaves the dryer.

As a simplification for calculation, the dryer is considered to be a heat exchanger. This assumption is not quite correct as there is not only the exchange of heat that must be considered but also the evaporation and therefore the mass transfer from wet wood to steam.
However, for a rough estimation this assumption should be adequate.

One of the major differences between these two kinds of flows is the difference in the average temperature throughout the whole dryer.

$$\Delta T_{counter} > \Delta T_{parallel} \qquad (10\text{-}21)$$

For calculating the average temperatures of concurrent and counter flow, the following equations are applied:

$$\Delta T_{parallel} = \frac{T_{steam,in} - T_{biomass,in} - (T_{steam,out} - T_{biomass,out})}{\ln \dfrac{T_{steam,in} - T_{biomass,in}}{T_{steam,out} - T_{biomass,out}}} \qquad (10\text{-}22)$$

$$\Delta T_{counter} = \frac{T_{steam,out} - T_{biomass,in} - (T_{steam,in} - T_{biomass,out})}{\ln \dfrac{T_{steam,out} - T_{biomass,in}}{T_{steam,in} - T_{biomass,out}}} \qquad (10\text{-}23)$$

Considering that the dryer is just a heat exchanger and that through the area (A_{exch}) the heat ($Q_{in,steam}$) is flowing, it is possible to compare these two types of operations. (A_{exch}) is the longitudinal area where the heat exchange takes place.

$$A_{exch} = D * L \tag{10-24}$$

Assuming that the heat exchange is constant on the whole length (L), the following equation could be applied:

$$\dot{Q}_{in,steam} = k \times A_{exch} \times \Delta T \tag{10-25}$$

$$k = \frac{\dot{Q}_{in,steam}}{A_{exch,\,parallel} \times \Delta T_{parallel}}$$

In the case of a parallel-flow dryer only k is unknown and can be calculated. With the same k, $Q_{in,steam}$ but with the temperature for $\Delta T_{counter}$, we receive the necessary area for a counter-flow dryer.

$$A_{exch,counterflow} = \frac{\dot{Q}_{in,steam}}{k \times \Delta T_{counter}} \tag{10.26}$$

The diameter will stay the same as for concurrent flow. Only the length will change.

$$L_c = \frac{A_{exch,counterflow}}{D} \tag{10.27}$$

The new length is always shorter than the length for a parallel-flow dryer because of the greater differences in temperatures and therefore faster evaporation.

11. Market overview

There are several companies which offer fluid or rotary dryers for applications used for wood-chips drying. The know-how of these dryers concerning its construction and technical solution has been gained by the concrete processing industry, the processing industry or the coal processing industry, at which these applications are used for drying, mixing or milling. Table 11.1 shows some of the companies using them, providing information on the type of dryer the company uses and the website address. The list is based on extensive internet research.

Nr.	**Company**	**Fluid dryer**	**Rotary dryer**	**Other dryer**	email address:
1	Allgier	X	X	X	www.allgaier.de
2	Arrowhead-Dryers		X	X	www.arrowhead-dryers.com
3	Atritor			X	www.atritor.com
4	Comessa	X	X	X	www.comessa.fr
5	Drytech Engineering	X	X	X	www.drytecheng.com
6	Heylpatterson	X	X	X	www.heylpatterson.com
7	Kason	X			www.kason.com
8	M.E.C. Company	X	X	X	www.m-e-c.com
9	Mitchell-dryers	X	X	X	http://mitchell-dryers.co.uk
10	Niro/Barr-Rosin	X	X	X	www.barr-rosin.com www.niro.com
11	Wolverineproctor	X		X	www.wolverineproctor.com

Table 11.1: Important dryer manufacturers

In order to gain further information regarding biomass dryers, the above named companies have been contacted and additional material requested. Unfortunately, only promotion material, which is already available on the companies' websites, was provided containing general information on the dryers. For detailed information about the price and design of a dryer it is necessary to fill in a specific form. A typical checklist facilitating the selection of industrial dryers will be given in the next chapter.

12. Main parameters affecting size, performance and cost

Considering a rough cost analysis for biomass plants it is noticeable that feed pre-treatment accounts for a big part of the total costs. The drying process itself accounts for approximately 12 percent of the total costs and is therefore an important part where wrong decisions might lead to a significant increase in the total price. The following table will show a cost analysis for an atmospheric pressure IGCC plant at 10 MWe.

Item	US$ million	%
Reception, storage and handling	2,5	12,5
Comminution and screening	1,5	7,5
Drying	2,5	12,5
Gasification	9	45
Heat recovery	1,5	7,5
Tar cracking/or removal	3	15
subtotal	20	100

Table 12.1 Approximate cost analysis of an atmospheric pressure IGCC plant at 10 MWe. [78]

In order to select the right dryer, a minimum of quantitative information is necessary which will be listed below.

- "*Dryer throughput; mode of feedstock production (batch/continuous)*
- *Physical, chemical and biochemical properties of the wet feed as well as desired product specifications; expected variability in feed characteristics*
- *Upstream and downstream processing operations*
- *Moisture content of the feed and product*
- *Drying kinetics; moist solid sorption isotherms*
- *Quality parameters (physical, chemical, biochemical)*
- *Safety aspects, e.g., fire hazard and explosion hazards, toxicity*
- *Value of the product*
- *Need for automatic control*
- *Toxicological properties of the product*

[78] Bridgwater; Butterworth & Heinemann Vol. 74 No.5; 1995; p. 634

- *Turndown ratio, flexibility in capacity requirements*
- *Type and cost of fuel, cost of electricity*
- *Environmental regulations*
- *Space in plant* “ [79]

12.1 Size

The construction of a dryer is subject to special regulations which are described as follows:

Volumetric load:

“*The overall hold-up bulk volume is usually in the range 3 to 12% of dryer volume, 7 to 8% being a common figure.*” [80] and according to the information provided by the company Heylpatterson: “*Most designers use a 15% volumetric load in the dryer.*” [81]

- Length/Diameter ratio

“*The length to diameter ratio of the shell usually lies between 4 and 10, with actual diameter ranging from <1 m to >6 m depending on throughput.*” [80]

“(…) *4 to 1 ratio of length to diameter is more typical of counter flow dryers. 10 to 1 ratios are more typical to parallel flow (co-current) dryers. Most parallel flow dryers are 6 to 1 ratio going up to 8 to 1. Very few are as long as 10 to 1.* “ [81]

Brammer and Bridgwater only roughly describe the length-diameter ratio, whereas the information of the Heylpatterson company is more precisely. The difference in the ratio for co-current dryers and counter flow dryers is about 1,5. Therefore, counter flow dryers are cheaper.
The design of a dryer with bigger diameter and shorter length is more expensive than the other way round. The factor which causes this situation is that it is more difficult and hence more expensive to go widthways in the construction.

[79] Cf. http://www.geocities.com/drying_guru/class.html (03.2007)
[80] Brammer, Bridgwater; 1999; p. 277
[81] Morris Jeffery W; information from Heylpatterson company

12.2 Costs

There is some rough information about dryer system costs given by the Heylpatterson company. Typical rotary dryer costs for a carbon steel construction would be:

diameter [m]	length [m]	costs [$]
1,5	9,1	400000
2,4	13,7	620000
3	16,8	850000
3,6	21,3	1200000

Table 12.2 Costs for different sizes of dryers from Heylpatterson

The above dryers include complete systems consisting of combustion system, fans, dust collectors, motors, controls and connecting ductwork.
More information about the costs of dryers with specification on biomass type, flow rate, moisture in and out, drying medium type, flow rate, dryer volume and power consumption is given in Brammer J.G. and Bridgwater A.V. [82]

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[82] Cf. Brammer, Bridgwater; Drying technologies for an integrated gasification bio-energy plant; Renewable and Sustainable Energy Reviews 3 (1999); Pages 243-289

13. Conclusion and outlook

With an actual photosynthesis efficiency of 3 percent or even less, the gap to the theoretical possible 8 percent is huge. In the future an increasing yield can be expected because of improvements in harvesting techniques and cultivation fields. The same situation is already given as regards corn yields. The continuously growing rates are still not sufficient in order to ensure the economic efficiency of future biomass conversion plants. Stronger increasing yields through plant modification and the fast growing plant breeding are the most promising ways to cover the demand for biomass. The positive aspects of higher yields include decreasing transportation costs to the conversion facility and smaller land requirements, at which the land resources are limited and are needed for food production.

A change from traditional food production farms to farms where energy crop cultivation takes place is possible because the farmers' incomes stay the same. Another positive aspect is that such energy plants are long-living and do not need to be planted annually. The nearer the biomass production facility is to the biomass conversion plant, the easier it is to set long-term strategies and to operate the facility as economical as possible.

The conversion processes which are used today achieve an efficiency that is comparable to those of coal and gas. In terms of generating electricity, the efficiency of such power plants is similar. In view of hydrogen production, only the gas reforming process reaches a significantly higher efficiency. The prices for fossil energy will rise continuously and further developments in conversion technology will make biomass competitive to fossil energy and other renewable energy sources. Photovoltaic, wind energy or CSP technology are at the moment to much depending on the weather conditions and are difficult to store which is not the case for biomass.

The use of biomass as energy resources demands pre-treatment before it can be converted into heat, electricity or liquid fuels. The calculation of a dryer includes some simplification in order to ensure a full understanding of the complex mathematical model. With an energy balance it is possible to find out how much energy has to be delivered through the superheated steam. The temperature of the drying medium, in this case of superheated steam, is limited at the inlet and outlet due to physical conditions. Thus, it is possible to calculate the amount of necessary steam. Taking into account the assumed demand of biomass flow and the related amount of superheated steam flow, the dimension of the dryer can roughly be calculated. The velocity of steam should be chosen between 3 and 7 m/s in order to avoid a recondensation or an entrainment of biomass material. The temperature differences are always higher in a counter flow dryer than in a parallel flow dryer and hence the biomass is drying faster. This can be seen by comparing the length differences of these two operating types. Transporting the same amount of biomass, the length of the counter flow dryer is less. This reduces construction costs and should be preferred if the biomass is not too sensitive to high temperatures.

In order to reassess the theoretical mathematical model, a test run would have to take place. This could involve a variation of both the steam velocity and the amount of biomass inlet.

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Table contents:

Figure- contents:

Symbols:

Symbols	Description	Units
A	area of solar cell, or	[m^2]
	Area of dryer	[m^2]
c	specific heat capacity	[kJ/kgK]
D	diameter	[m]
E	light irradiance	[W/m^2]
F	diffusion coefficient	[m^2/s]
g	acceleration due to gravity	[m/s^2]
h	specific enthalpy	[kJ/kg]
H	heat accumulation	[J/m^3]
K	absolute permeability	[m^2]
L	length	[m]
m	mass flux	[kg/s]
M	Mass accumulation	[kg/m^3]
M_w	molecular weight of water	[kg/mole]
Nu_x	Nusselt number	-
p	pressure	[Pa]
P	power	[W]
p_c	capillary pressure	[Pa]
Pr	Prandtl number	-
q	heat flux	[J/m^2s]
Q	heat	[kW]
R	gas constant	[J/moleK]
Re	Reynolds number	-
R_{rotor}	Rotor diameter	[m]
t	time	[s]
T	Temperature	K
v	velocity	[m/s]
x	distance	[m]
X	moisture content	[kg water/kg dry wood]
Y	molar fraction	-
μ	dynamic viscosity	[kg/ms]
ρ	density	[kg/m^3]
σ	Bolzmann's constabt	[W/m^2K^4
ε	emissivity	-

Subscripts	
α	ambient
κ	component
g	gas
l	liquid
sat	saturation
th	bound or thikness of the wood chip
eff	effective
s	steam
b	biomass
w	water
v	evaporation

Abbreviation:

Abbreviations	Description
PAR	Photosynthetically Active Radiation
HHV	High Heating Value
SRC	Short Rotation Coppice
PME	Vegetable Methyl Ester
ETE	Effective Thermal Efficiency
EIA	Energy Information Administration
EU	European Union
SHF	Separate hydrolysis and fermentation
SSF	Simultaneous saccharification and fermentation
DMC	Direct microbial conversion
mc-Si	metal-semiconductor Silicon
PV	Photovoltaic
CSP	Concentrating Solar Power
SEGS	Solar Electricity Generation System
OECD	Organisation for Economic Cooperation and Development
daf	dry, ash free tonnes
FSP	Fibre Saturation Point
IGCC	Integrated Gasification Combined Cycle

Appendix 1: Actual values for average insolation

Country	State/City	Year Avg [kWh/m²day]	Average insolation [W/m²]	Yield [t/hm²yr]
AT	Vienna	3,52	146,7	211
ES	Madrid	4,62	192,5	278
F	Paris	3,34	139,2	201
IT	Milan	3,33	138,8	200
N	Oslo	2,27	94,6	136
UK	Edinburgh	2,26	94,2	136
USA	Los Angeles	5,40	225,0	324
USA	Miami	5,26	219,2	316
USA	Chicago	3,72	155,0	223
USA	Minneapolis	3,68	153,3	221
USA	New York	3,53	147,1	212
USA	Houston	4,72	196,7	284
EG	Cairo	5,68	236,7	341
TN	Tunis	4,70	195,8	282
AR	Buenos Aires	4,39	182,9	264
BR	Brasilia	5,03	209,6	302
BO	Sucre	3,93	163,8	236
PY	Asuncion	4,68	195,0	281
PE	Lima	3,71	154,6	223
VE	Caracas	5,59	232,9	336
CAN	Edmonton	3,37	140,4	202
CAN	Toronto	3,44	143,3	207
CAN	Montreal	3,37	140,4	202
AU	Melbourne	4,34	180,8	261
AU	Perth	5,16	215,0	310
CN	Shanghai	4,01	167,1	241
IN	New Delhi	5,10	212,5	306
KR	Seoul	4,16	173,3	250
TR	Ankara	4,17	173,8	250
NZ	Auckland	4,34	180,8	261
MY	Kuala Lumpur	4,70	195,8	282

Appendix 2: Arrangement of areas in Europe

Country	State/City	Year Avg [kWh/m²day]	Average insolation [W/m²]	Yield [t ha^{-1} yr^{-1}]
AT	Vienna	3,52		
HU	Budapest	3,17		
DE	Munich	2,98		
	sum of annual Avg.	3,22	134,3	194
	chosen as middle Europe with:		135	
BE	Brussels	3,02		
NL	Amsterdam	2,67		
NO	Oslo	2,27		
	sum of annual Avg.	2,65	110,6	159
	chosen as north-mainland Europe with:		106	
ES	Madrid	4,62		
ES	Malaga	5,16		
ES	Alicante	4,94		
	sum of annual Avg.	4,91	204,4	295
	chosen as south Europe with:		200	
IE	Dublin	2,39		
UK	Edinburgh	2,26		
UK	London	2,61		
	sum of annual Avg.	2,42	100,8	145
	chosen as north-island Europe with:		106	

Note: selected places/areas in Europe with HHV=17,5 MJ/kg, max. net efficiency 8 percent

Appendix 3: Properties of biomass

Type of biomass	Moisture % dry basis	Net calorific value MJ/kg	Total ash % dry basis	Volatile compounds
Sprucewood (with bark)	20-55	18.8	0.6	82.9
Beech-wood (with bark)	20-55	18.4	0.5	84.0
Poplar wood (Short rotation)	20-55	18.5	1.8	81.2
Willow wood (Short rotation)	20-55	18.4	2.0	80.3
Bark (softwood)		19.2	3.8	77.2
Rye straw		17.4	4.8	76.4
Wheat straw	15	17.2	5.7	77.0
Triticale straw	15	17.1	5.9	75.2
Barley straw	15-30	17.5	4.8	77.3
Rape straw	15	17.1	6.2	75.8
Corn straw	15	17.7	6.7	76.8
Sunflower straw	15	15.8	12.2	72.7
Hemp straw	15	17.0	4.8	81.4
Rice straw Husk	15	12.0 14.0	4.4 19.0	
Groundnut shells	3-10	16.7	4-14	
Coffee husks	13	16.7	8-10	
Cotton husks	5-10	16.7	3	
Coconut husks	5-10	16.7	6	
Oil palm husks	55	8.0	5	
Rye whole crop		17.7	4.2	79.1
Wheat whole crop		17.1	4.1	77.6
Triticale whole crop		17.0	4.4	78.2
Miscanthus	11,5	17.6	3.9	77.6
Rye grain		17.1	2.0	80.9
Wheat grain		17.0	2.7	80.0
Triticale grain		16.9	2.1	81.0
Rape grain		26.5	4.6	85.2
Olives (pressed)	15-18	16.7	3	
Corncobs	15	13.4	15-20	
Sugar cane stalk (bagasse)	40-50	8.0	4.0	80
Hay from various sources		17.4	5.7	75.4
Road side green		14.1	23.1	61.7
Hard coal		29.7	8.3	34.7
Lignite	50	20.6	5.1	52.1