

## Chapter 2

# Biomass Availability, Potential and Characteristics

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**Abstract** Biomass refers to any organic materials that are derived from plants (including algae, trees and crops) and comprises material which has an organic origin. This leads to a wide range of possible sources of biomass each with their own composition and to different possible classifications. In the energy field, “biomass” refers to the organic matter (living or residue) that can be used as combustible material or energy source for power generation, heat or biofuels. After a description of the main types of biomass used in the energy field, their composition is given and the main parameters to evaluate their energy potential are listed and commented. In particular, the energy potential of virgin biomass, both terrestrial and aquatic, and waste biomass is investigated. An analysis on the availability of the biomass is outlined together with its worldwide productivity. Finally, a list of limitation of energy production from this resource related to historical, technical, economic, environmental and social reasons is described.

### 2.1 Biomass Definition and Classification

In a broad sense, biomass is defined as the whole organic matter produced by biological processes. In the energy field, “biomass” refers to the organic matter (living or residue) that can be used as combustible material or energy source for power generation, heat or biofuels. The plethora of biomass suggests a huge variety of classifications. The first distinction is based on differentiation upon animal and plant biomass. The use of animal biomass for energy purposes is always considered a secondary matter for two reasons:

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- Animal beings are heterotrophic organisms, feeding themselves directly or indirectly with organic matter produced by autotrophic organism (plant beings). Therefore the energy inside animal matters always derives from plant organisms;
- Animal biomass usable for power energy consists of remaining portions of other activities, mainly wastes and livestock excrements. That is, energy from animal biomass is a necessary outcome of other activities linked to the production of energy.

Differently from animal beings, autotrophic organisms as vegetables algae and some kinds of bacteria produce organic matters which they need from inorganic substances and are able to convert the energy from solar radiation into chemical energy. Plant organisms can be used not only as food but also for processes dedicated to energy production. The energy produced in such processes is sun-derived. This chapter is dedicated to vegetal biomass as, capturing solar energy, it can realize a renewable energy supply.

Common sources of biomass are:

- *Agricultural*: food grain, bagasse (crushed sugarcane), corn stalks, straw, seed hulls, nutshells, poultry and hogs;
- *Forest*: trees, wood waste, wood or bark, sawdust (SW), timber slash and mill scrap;
- *Municipal*: municipal solid waste (MSW), sewage sludge, refuse-derived fuel, food waste, waste paper and yard clippings;
- *Energy crops*: poplars, willows, switch grass, corn, soybean, canola and other plant oils;
- *Biological*: animal waste, aquatic species and biological waste.

### **2.1.1 Types of Biomass**

Biomass refers to any organic materials that are derived from plants (including algae, trees and crops) (McKendry 2002) and comprises material which has an organic origin. Biomass does not include organic materials that over many millions of years have been transformed by geological processes into fossil fuels such as coal or petroleum. The definition of biomass for energy given in the European Directive 2009/28/EC is the following: “the biodegradable fraction of products, waste and residues from biological origin from agriculture (including vegetal and animal substances), forestry and related industries including fisheries and aquaculture, as well as the biodegradable fraction of industrial and municipal waste”. This leads to a wide range of possible sources of biomass each with their own composition. Different classifications are possible and were published. European committee for standardization published two standards for classification and specification (EN 14961) and quality assurance (EN 15234) of biomass. Based on

their origin, it classified biomass under four main categories (McKendry 2002; Williams et al. 2001):

- Woody plants. A woody plant is a vascular plant that has perennial stem that is above ground and covered by a layer of thickened bark. Woody plants contain wood, which is composed of structures of tightly bound fibres of cellulose and lignin (trees, bushes, shrubs ...);
- Herbaceous plants. An herbaceous plant is a plant that has leaves and stems that die down at the end of the growing season to the soil level. These plants do not contain wood; therefore, their structure is composed of more loosely bound fibres of lignin and cellulose. This also means that the lignin content for herbaceous plants is lower than for woody plants (grasses, stalk, straw, grains and cereals);
- Aquatic plants. Aquatic plants are plants, which grow underwater like kelp and algae. The moisture content of this type of biomass is usually high (e.g. kelp);
- Wastes. Wastes are all kinds of waste streams, like manure, sewage sludge, refused-derived fuel (RDF). Most of the wastes are extremely wet, like sewage sludge and moisture manure (sewage sludge, refuse-derived fuel and animal wastes).

Loosely speaking, biomass includes all plants and plant-derived materials, including livestock manures. Primary or virgin biomass comes directly from plants or animals. Waste or derived biomass comes from different biomass-derived products. Table 2.1 (Klass 1998) lists a range of biomass types grouping them into two broad group, virgin or waste:

1. Virgin biomass includes wood, plants, leaves (lignocellulose), and crops and vegetables (carbohydrates).
2. Waste biomass includes solid and liquid wastes (municipal solid waste); sewage, animal and human wastes; gases derived from landfilling (mainly methane); and agricultural wastes.

### **2.1.1.1 Virgin Biomass**

Considering the incident solar radiation, or insolation, that strikes the earth's surface, at an average daily insolation worldwide of about  $220 \text{ W/m}^2$ , the annual insolation on about 0.01% of the earth's surface is approximately equal to all the primary energy consumed by humans each year (Klass 1998). The most widespread and practical process for capture of this energy as organic fuels is the growth of virgin biomass. Extremely large quantities of carbon are fixed each year in the form of terrestrial and aquatic biomass. Using the figures in Table 2.1, the energy content of standing biomass carbon; that is, the renewable, above-ground biomass reservoir that in theory could be harvested and used as an energy resource, is about 100 times the world's annual energy consumption.

**Table 2.1** Estimated net photosynthetic production and carbon storage in biomass (Consonni 2006)

Ecosystem	Area		Average net production of carbon			Carbon stored in biomass			Stored/production rate	
	10 <sup>6</sup> km	%	t/(ha-year)	10 <sup>9</sup> t/year	%	t/ha	10 <sup>9</sup> t	%	Years	
Tropical pluvial forest	17	11.4	9.9	16.83	32.8	202.5	344.25	41.6	20.5	
Boreal forest	12	8.1	3.6	4.32	8.2	90	108	13	25	
Tropical seasonal forest	7.5	5	7.2	5.4	10.2	157.5	118.13	14.3	21.9	
Temperate decidual forest	7	4.7	5.4	3.78	7.2	135	94.5	11.4	25	
Evergreen temperate forest	5	3.4	5.85	2.93	5.5	157.5	78.75	9.5	26.9	
Total forest	48.5	32.6		33.26	62.9		743.63	89.8	22.4	
Extreme desert, sand, rocks	24	16.1	0.01	0.02	0	0.1	0.24	0	10	
Shrub deserts and semi-deserts	18	12.1	0.41	0.74	1.4	3.2	5.76	0.7	7.8	
Savanna	15	10.1	4.05	6.08	11.5	18	27	3.3	4.4	
Cultivated land	14	9.4	2.93	4.1	7.8	4.5	6.3	0.8	1.5	
Temperate grasslands	9	6	2.7	2.43	4.6	7.2	6.48	0.8	2.7	
Woods and shrubs	8.5	5.7	3.15	2.68	5.1	27	22.95	2.8	8.6	
Tundra and mountain regions	8	5.4	0.63	0.5	1	2.7	2.16	0.3	4.3	
Marshes and swamps	2	1.3	13.5	2.7	5.1	67.5	13.5	1.6	5	
Lakes and rivers	2	1.3	1.8	0.36	0.7	0.1	0.02	0	0.1	
Total emerged lands	100.5	67.4		19.61	37.1		84.41	10.2	4.3	
Total continental	149	100		52.87	100		828.04	100	15.7	
Open Ocean	332	89.5	0.56	18.59	70.9	0.1	3.32	73.1	0.2	
Continental platform	36.6	9.9	1.62	5.93	22.6	0	0.01	0.3	0	
Estuaries, swamps excluded	1.4	0.4	6.75	0.95	3.6	4.5	0.63	13.9	0.7	
Alga beds and coral barrels	0.6	0.2	11.25	0.68	2.6	9	0.54	11.9	0.8	
Emergent lands	0.4	0.1	2.25	0.09	0.3	0.9	0.04	0.8	0.4	
Total seas	371	100		26.23	100		4.54	100	0.2	
General total	520		79.1			832.58			10.53	

**Table 2.2** Estimated distribution of World's biomass carbon (adapted from Table 2.1)

	Forests	Savanna and grasslands	Swamp and marsh	Remaining terrestrial	Marine
Area ( $10^6 \text{ km}^2$ )	48.5	24.0	2.0	74.5	361
Percent, %	9.5	4.7	0.4	14.6	70.8
Net C production (Gt/year)	33.26	8.51	2.70	8.40	24.62
Percent, %	42.9	11.0	3.5	10.8	31.8
Standing C (Gt)	744	33.5	14.0	37.5	4.5
Percent, %	89.3	4.0	1.7	4.5	0.5

Each ecosystem on the earth is considered in terms of area, mean net carbon production per year, and standing biomass carbon. Standing biomass carbon is that contained in biomass on the earth's surface and does not include the carbon stored in biomass underground. Condensing these data in Table 2.2, the interpretation is earlier: of the total net carbon fixed on the earth each year, forest biomass, which is produced on only 9.5% of the earth's surface, contributes more than any other source. Marine sources of net fixed carbon are also high, as might be expected because of the large area of the earth occupied by water. But the high turnover rates of carbon in a marine environment result in relatively small steady-state quantities of standing carbon. In contrast, the low turnover rates of forest biomass make it the largest contributor to standing carbon reserves. According to the Table 2.2, the forests produce about 43% of the net carbon fixed each year and contain over 89% of the standing biomass carbon of the earth. Tropical forests are the largest sources of these carbon reserves. Temperate deciduous and evergreen forests are also major sources of biomass carbon. Next in order of biomass carbon supply would probably be the savanna and grasslands.

## Terrestrial

### *Forest biomass*

About one-third of the world's land area is forestland. Broad-leaved evergreen trees are a dominant species in tropical rain forests near the equator. In the northern hemisphere, stands of coniferous, softwood trees such as spruce, fir and larch dominate in the boreal forests at the higher latitudes, while both the broad-leaved deciduous hardwoods such as oak, beech and maple and the conifers such as pine and fir are found in the middle latitudes. Although the prime purpose is to produce wood fibre for the manufacture of paper products, the pulp and paper companies have operated large tree plantations that yield energy as a by-product for decades. Heat, steam and electricity are produced from wood wastes and also black liquor which is generated in the paper manufacturing process.

One of the tree species that has been studied in great detail as a renewable energy resource is the eucalyptus, evergreen hardwood trees that belong to the myrtle

family. The eucalyptus is a rapidly growing tree native to Australia and New Guinea, and Hawaii for a variety of construction purposes. It appears to be a prime candidate for energy use because it reaches a size suitable for harvesting in about 7 years (Klass 1998).

### *Grasses*

Grasses are very abundant forms of biomass. About 400 genera and 6000 species are distributed all over the world and grow in all land habitats capable of supporting higher forms of plant life (Klass 1998). Grass family (Gramineae) includes the great fruit crops, wheat, rice, corn, sugarcane, sorghum, millet, barley and oats. Grass also includes the many species of sod crops that provide forage or pasturage for all types of farm animals. Grasses are grown as farm crops, for decorative purposes, for preserving the balance of productive capacity of lands by crop rotation, for controlling erosion on sloping lands, for the protection of watersheds and for the stabilization of arid areas. Perennial grasses have been suggested as candidate feedstocks for conversion to synfuels. Most perennial grasses can be grown vegetatively, and they re-establish themselves rapidly after harvesting. Moreover, more than one harvest can usually be obtained per year.

### *Aquatic*

With the exception of phytoplankton, which generally has lower net productivities, aquatic biomass seems to exhibit higher net organic yields than most terrestrial biomass. Aquatic biomass species that are considered to be the most suitable for energy applications include the unicellular and multicellular algae, freshwater plants and marine species.

### *Algae*

Microalgae are prokaryotic or eukaryotic photosynthetic microorganisms that can grow rapidly and live in harsh conditions due to their unicellular or simple multicellular structure. Microalgae are present in all existing earth ecosystems, not just aquatic but also terrestrial, representing a big variety of species living in a wide range of environmental conditions. It is estimated that more than 50,000 species exist, but only a limited number, of around 30,000, have been studied and analysed (Mata et al. 2010). They have been under development as renewable energy resources and other useful products for a long time. For the past 50 years, extensive research has been performed on microalgae and how they can be used in a wide variety of processes or to manufacture many practical and economic important products. The first large-scale culture of microalgae started in the early 1960s in Japan by Nihon Chlorella with the culture of Chlorella. Other common types of microalgae are Dunaliella, Nannochloropsis, Scenedesmus and Spirulina. Microalgae cultivation can be done in open-culture systems such as lakes or ponds and in highly controlled closed-culture systems called photo-bioreactors (PBR). Open-culture systems are normally less expensive to build and operate, more

durable than large closed reactors and with a large production capacity when compared with closed systems. On the other hand, PBRs are flexible systems that can be optimized according to the biological and physiological characteristics of the algal species being cultivated, allowing one to cultivate algal species that cannot be grown in open ponds. Depending on their shape or design, PBRs are considered to have several advantages over open ponds: offer better control over culture conditions and growth parameters (pH, temperature, mixing, CO<sub>2</sub> and O<sub>2</sub>), prevent evaporation, reduce CO<sub>2</sub> losses, allow to attain higher microalgae densities or cell concentrations, higher volumetric productivities, offer a more safe and protected environment, prevent contamination or minimize invasion by competing microorganisms. Despite their advantages PBRs suffer from several drawbacks that need to be considered and solved. Their main limitations include: overheating, bio-fouling, oxygen accumulation, difficulty in scaling up, the high cost of building, operating and of algal biomass cultivation, and cell damage by shear stress and deterioration of material used for the photo-stage.

Nowadays, microalgae are seen as an alternative feedstock for biodiesel production. Recent research efforts have concentrated on applying metabolic engineering and genetic methods to microalgae in order to develop organisms optimized for high productivity and energy value, in order to achieve their full processing capabilities (Mata et al. 2010). Since microalgae do usually have no cell differentiation, genetic manipulations to increase its content of higher value compounds is very tempting. Nevertheless, progress in the genetic engineering of algae was extremely slow until recently and these promising advances should be viewed with caution because transgenic algae potentially pose a considerable threat to the ecosystem and thus will most likely be banned from outdoor cultivation systems.

### *Water Plants*

The productivity of some salt marshes is similar to that of seaweeds. Their annual organic productivity on optimum sites is about 30–35 t/(ha-year) for *Spartina alterniflora* and emergent communities in brackish water (Klass 1998) but there are not sufficient information available to judge their value in biomass energy systems. Other species such as *Arundo donax*, *Scirpus lacustris* and Cattail, if can be sustained, should be suitable candidates for biomass energy usage.

### **2.1.1.2 Waste Biomass**

Another large source of renewable carbon supplies is waste biomass. Waste biomass is energy-containing materials that are discarded or disposed of and that are mainly derived from or have their origin in virgin biomass. It is generated by anthropological activities and some natural events. As it is derived from primary biomass like trees, vegetables, meat during the different stages of their production or use, it is defined secondary biomass. It consists of a wide range of materials and includes municipal solid waste (MSW), municipal biosolids (sewage), industrial

waste, animal manures, agricultural crops and forestry residues, landscaping and tree clippings and trash, and dead biomass that result from nature's life cycles. They are lower in costs than virgin biomass and often have negative costs.

## Municipal Wastes

There are basically two types of municipal wastes that offer opportunities for combined waste disposal and energy recovery.

### *Municipal solid waste—MSW*

As the populations of urban areas grow, the production of MSW increases, sometimes in a disproportional way. The collection and disposal costs increase and proper disposal becomes more difficult to achieve with the passage of time. At the same time, the loss of natural resources in the MSW occurs if no effort is made to recover them. The opportunities for combined waste disposal and energy recovery are thus evident. The major part of MSW comes from renewables like food scraps, lawn clippings, leaves and papers. Non-renewable components of MSW like plastics, glass and metals are not considered biomass. Thus, waste biomass is a potential energy resource in the same manner as virgin biomass.

To assess the **energy potential** from waste biomass on supplying energy demand, it is necessary to consider the amounts of different types of wastes generated, their energy contents and their availabilities. In 2013, in Europe, the total amount of MSW was about 243.2 Million of tonnes (ISPRA 2015). Every person, discards about 1.5 kg of MSW per day (2013) distributed as shown in Table 2.3.

From an energy standpoint, one short tonne of MSW has an as-received energy content of about 9.5 GJ, so about 4.2 EJ/year of energy potential resides in the MSW generated in Europe.

### *Biosolids*

Municipal wastewater treatment plants in industrialized countries receive wastewaters from residential sources, industry, groundwater infiltration and stormwater runoff. The pollutants associated with these sources include a wide range of suspended and dissolved compounds and oxygen-demanding materials, many of which are toxic. Pathogenic components are present, including certain bacteria, viruses, organic compounds, inorganic nutrients and heavy metals. The purpose of most wastewater treatment processes is to remove or reduce these components, other pollutants and biological oxygen demand before discharge to receiving waters. Primary biosolids (settleable and suspended solids) are present at a level of a few percent in the influent wastewater.

The **energy potential** of municipal biosolids is small. At an average higher heating value (HHV) of 19.9 MJ/kg<sub>dm</sub> (Klass 1998), the energy content of all the primary and treated biosolid produced in 2005 in Europe (Iranpour et al. 2000) can be estimated to be around 0.166 EJ/year, much less than the energy potential of MSW.



**Table 2.3** MSW pro capite in Europe, 2013

Country	MW produced	MW treated	MW treated (%)			
	(kg/year) pro capite	(kg/year) pro capite	Recycling	Composting	Incineration	Landfill
UE28	481	470	28	15	26	31
UE15	521	517	29	16	29	26
Belgium	439	440	34	21	44	1
Bulgaria	432	428	25	3	2	70
Czech Republic	307	307	21	3	20	56
Denmark	747	747	28	17	54	2
Germany	617	617	47	17	35	0
Estonia	293	253	14	6	64	16
Ireland	586	531	34	6	18	42
Greece	510	510	16	4	0	81
Spain	449	449	20	10	10	60
France	530	530	21	17	34	28
Croatia	404	393	14	2	0	85
Italy	491	474	26	15	21	38
Cyprus	624	624	12	9	0	79
Leetonia	312	312	11	6	0	83
Lithuania	433	421	21	8	7	64
Luxembourg	653	653	28	20	35	17
Hungary	378	378	21	5	9	65
Malta	570	526	6	5	0	88
The Netherland	526	526	24	26	49	1
Austria	578	559	25	34	36	4
Poland	297	249	16	13	8	63
Portugal	440	440	13	13	24	50
Romania	272	220	3	0	0	97
Slovenia	414	287	55	7	1	38
Slovakia	304	278	4	8	12	77
Finland	493	493	19	14	42	25
Sweden	453	453	34	15	50	1
UK	482	476	28	16	21	35

### Agricultural Solid Wastes

Application of animal wastes to land is one of the most economical choices for disposal as well as providing fertilizing benefits. However, the utilization of live-stock and poultry manures as waste biomass resources for energy applications could

help mitigate pollution and at the same time open new markets. Agricultural crop residues are also examined.

### *Livestock and poultry manures*

Intuitively, high populations of specific animals would be expected to offer the greatest opportunity to serve as sources of waste biomass because waste generation is maximized. Because of the relationship of waste productivity and animal size, this is not always the case as will be shown here. Domestic farm animals and those confined to feedlots are appropriate choices. The animals that produce large, localized quantities of excreta are cattle, hogs and pigs, sheep and lambs and poultry.

The **energy potential** of each category can be derived from the heating values estimated by Stanford Research Institute (Stanford Research Institute 1976) and reported in Table 2.4.

### *Agricultural crop residues*

Agricultural crop residues are those left in the field or accumulated during sorting and cleaning of produce. Being a predominantly agricultural-based economy, large quantities of biomass residues from the crop are generated throughout the country. It is a common practice to burn the residues in cultivated fields as a means of agricultural land preparation. Residues that are also generated from agricultural processing facilities are burdensome to processors because of costs incurred in their disposal. However, their use as an energy source is still very limited in the country. One of the most important steps in developing biomass energy supply from residue is to evaluate their spatial and temporal availability. Such an analysis would provide useful information for decision-makers on the opportunities for using biomass residues for energy application in the country.

Here the focus is on biowastes related to some of the main food crops of Southern Europe, which are known to yearly generate very large amounts of biowastes according to the Food and Agriculture Organization of the United Nations (FAO). FAO reported that the top five primary earth products of South Europe in 2012 were wheat, grapes, tomatoes, sugar beet and olives, which were produced as shown in Table 2.5 together with the heating value.

Because of the discontinuity in growing seasons, many crops that are grown, differences between specific crops, variation in crop yields in different areas,

**Table 2.4** Heating values of livestock/poultry (Stanford Research Institute 1976)

Livestock/poultry	Heating value (MJ/dry kg)
Cattle	15.73
Hogs and pigs	16.99
Sheep and lambs	17.82
Chickens	13.53
Commercial broilers	13.53
Turkeys	13.49

**Table 2.5** Production of target crops and related wastes in South Europe according to reviewed literature (FAO 2009 and 2012)

Earth product	Mt	Solid wastes	Mt	Heating value (MJ/kg)
Olives	9.31	Olive pomace	4.5–10	14.6–16.7 (Intelligent Energy EUROPE 2010)
Grapes	13.92	Grape pomace	1.3–2.8	16.1–18.9 <sup>a</sup> (Burg et al. 2016)
Tomatoes	12.13	Tomato pomace	0.1–0.2	23.77 (Tillman and Jahn 2016)
Sugar beets	9.76	Sugar beet pulp	0.5–1.5	3.20 (Akram et al. 2015)

<sup>a</sup>Lower calorific values were determined in the pomace after separation of the seeds: 14.60–17.75 MJ/kg, whereas the highest calorific values were determined in the seeds themselves, i.e. 19.78–21.13 MJ/kg

difficulty of acquiring reliable data and long-term time effects, an inventory of the annual production of agricultural crop residues and their disposition might seem to be an impossible task. Fairly reliable data can, however, be obtained estimating a residue factor defined as the ratio of a field weight of residue per mass unit of crop yield. The quantity of residue generated will be the product of the residue factor and the country yield total for that crop.

To estimate the **energy potential** of crop residues, several parameters are needed, namely, annual crop production and the residue availability, dry weight and ash factors. In literature, for the selected residues, the energy potential is shown in Table 2.5.

## Forestry Residues

Forestry residues consist of slash left on the forest floor following logging operations; stems, stumps, tops, foliage and damaged trees that are not merchantable, wood and bark residues accumulated at primary wood manufacturing plants during production of lumber. Underground tree roots can also be included in the list of forestry residues. The difficulty of accurately assessing the amounts of forestry residues that are and can be realistically collected and utilized as waste biomass for an entire country has been encountered by almost all who have embarked on the task (Klass 1998). Regional forest offices, for example, do not keep and maintain detailed records of residues production and its disposition; surveys that are done periodically and for different countries for a given time period are subject to considerable error.

Table 2.6 lists the composition and heating values of some waste biomass products.

### 2.1.2 Chemical–Physical Composition

A proper understanding of the physical and the chemical properties of biomass feedstock is essential for the design of a reliable biomass conversion system.

**Table 2.6** Typical composition of some waste biomass (Basu 2013)

Biomass	Moisture (wt%)	Organic matter (dry wt%)	Ash (dry wt%)	HHV (MJ/dry kg)
Cattle manure	20–70	76.5	23.5	13.4
Sewage	90–98	73.5	26.5	19.9
RDF	15–30	86.1	13.9	12.7
Sawdust	15–60	99.0	1.0	20.5

**Table 2.7** Typical composition of different biomass species (Adapted from Vigouroux 2001)

Species	Cellulose	Hemicellulose	Lignin	Extractives	Ash
Scandinavian Birch <sup>a</sup>	40.0	39.0	21.0	n.a.	0.3
Softwood <sup>a</sup> (average)	45.8	24.4	28.0	n.a.	1.7
Hardwood <sup>a</sup> (average)	45.2	31.3	21.7	n.a.	2.7
Scandinavian pine	40.0	28.5	27.7	3.5	n.a.
Wood bark <sup>a</sup>	24.8	29.8	43.8	n.a.	1.6
Bagasse <sup>b</sup>	41.8	22.9	18.5	13.9	2.9
Coconut shell <sup>b</sup>	36.6	25.3	29	8.4	0.7
Corn stalks <sup>b</sup>	42.7	23.6	17.5	9.8	6.8
Olive husk <sup>a</sup>	24.0	23.6	48.4	n.a.	4.0
Wheat straw <sup>b</sup>	34.1	32.3	18.3	2.7	12.5
Rice husk <sup>b</sup>	30.7	23.9	14	8.3	23.1
Rice straw <sup>b</sup>	43.9	27	3.1	2.5	23.5

*n.a.* not analysed

<sup>a</sup>wt% dry and extractive free basis

<sup>b</sup>wt% dry basis

This chapter discusses some important properties of biomass that are relevant to such processes.

As far as it regards chemical–physical composition, the main materials constituting plant biomass are lignin and carbohydrates, structural support of wood plants. Carbohydrates are also divided in cellulose and hemicellulose. Long polymers of cellulose constitute the fibres which provide mechanical strength for plant structure, while lignin works as fibre glue; hemicellulose is the cementing matter of the wood parts. There may be also a broad variety of chemical compounds (resins, waxes, fats, oils, amid, sugar, tannic substances and pigments, etc.) whose name derives from the capability of being extracted with solvents. There are also small quantities of inorganic matter constituted with alkaline species (Na, K, Mg, Ca), heavy metals (Cd, Zn, As, Pb, Cu, etc.) and S, Cl, N, P, Si, Al, etc.; the remaining matter of combustion is ash. Table 2.7 points out the composition of some important species for food or industrial production, while the Table 2.8 points out variation ranges of the three main components.

**Table 2.8** Cellulose/lignin content of selected biomass (wt%) (McKendry 2002)

Biomass	Lignin (%)	Cellulose (%)	Hemicellulose (%)
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

### 2.1.3 Composition of Biomass

Biomass contains a large number of complex organic compounds, moisture, and a small amount of inorganic impurities known as ash. The organic compounds comprise four principal elements: carbon (C), hydrogen (H), oxygen (O) and nitrogen (N). Biomass (e.g. MSW and animal waste) may also have small amounts of chlorine (Cl) and sulphur (S). The latter is rarely present in biomass except for secondary sources like demolition wood, which comes from torn-down buildings and structures.

Thermal design of a biomass utilization system, whether it is a gasifier or a combustor, necessarily needs the composition of the fuel as well as its energy content. In the context of thermal conversion like combustion, the following two types of compositions are mostly used:

1. Proximate composition.
2. Ultimate or elemental composition.

Besides these, there is also the polymeric composition of biomass, which is important for chemical conversions like torrefaction, pyrolysis and gasification.

Important properties for energy conversion processes of woody and herbaceous plants are:

- The moisture content: high moisture is a major characteristic of biomass. The root of a plant biomass absorbs moisture from the ground and pushes it into the sapwood. The moisture travels to the leaves through the capillary passages. Photosynthesis reactions in the leaves use some of it, and the rest is released to the atmosphere through transpiration. For this reason, there is more moisture in the leaves than in the tree trunk.
- Heating value: it represents the heating value when the biomass is combusted. This heating value can be defined in different two ways: HHV and lower heating value (LHV).
- Proportion of fixed carbon and volatiles: the volatile matter of a fuel is the condensable and non-condensable vapour released when the fuel is heated. Its amount depends on the rate of heating and the temperature to which it is heated.
- The ash/residue content: Ash is the inorganic solid residue left after the fuel is completely burned. Its primary ingredients are silica, aluminium, iron and calcium; small amounts of magnesium, titanium, sodium and potassium may also be present. The ash content of biomass is generally very small but may play a

**Table 2.9** Average property values for specified biomass groups (Phyllis ECN)

Property	Woody plants	Herbaceous plants	Aquatic plants	Wastes
<i>Example</i>	<i>Untreated wood</i>	<i>Grass/plant</i>	<i>Algae</i>	<i>Manure</i>
Moisture content (wt% wet)	18.6	29.8	31.9	74
Lower heating value <sup>a</sup> (kJ kg <sup>-1</sup> )	18,772	18,298	23,147	18,906
Fixed carbon <sup>a</sup> (wt%)	18.1	17.5	14.8	19.1
Volatile matter <sup>a</sup> (wt%)	81.9	82.5	85.2	80.9
Ash content <sup>b</sup> (wt%)	2.2	6.9	6.1	28.5
Cellulose content <sup>b</sup> (wt%)	39.8	43.9	30	23.1
Hemicellulose content <sup>b</sup> (wt%)	23.3	19.7	35	26.7
Lignin content <sup>b</sup> (wt%)	24.8	10.9	–	11.3

<sup>a</sup>The values are on dry ash free (daf) basis

<sup>b</sup>The values are on dry basis

significant role in biomass utilization especially if it contains alkali metals such as potassium or halides such as chlorine. Straw, grasses and demolition wood are particularly susceptible to this problem. These components can lead to serious agglomeration, fouling and corrosion in boilers or gasifiers.

- The alkali metal content: many biomass types among the agricultural residues show high contents of alkali salts, in particular potassium based (straw, perennial grasses). When the temperature exceeds approximately 700 °C, these (eutectic) salts are evaporated into the gas phase (Stevens 2001).
- The cellulose/lignin ratio: the cellulose and lignin are important in biochemical processes, because the biodegradability of cellulose is greater than of lignin. This is important for the selection of plants for biochemical conversion.

In dry biomass conversion processes, the first five properties are important. While for wet biomass conversion processes, the first and the last property are of more importance.

Because of the diverse nature of biomass, properties in these categories can vary widely (Williams et al. 2001; Khan 2007). In Table 2.9, some average values of properties are given for specified biomass groups (Phyllis ECN).

### 2.1.3.1 “Proximate” Analysis

Proximate analysis gives the composition of the biomass in terms of gross components such as moisture, volatile matter, ash and fixed carbon. It is a relatively simple and inexpensive process.

Two fundamental characteristics which discriminate the technology suitable for the production of energy coming from biomass are the humidity content and volatile matter. *Moisture* can be present in biomass in two ways:

- Intrinsic is the moisture captured within the biomass, e.g. the content of water which does not depend on whether condition since it is deeply linked to the structure of the biomass. It is hard to remove;
- Extrinsic is the moisture which is influenced by the weather condition during harvesting, e.g. the water content determined from the weather condition present during the harvest. This type of moisture is easy to remove.

The extrinsic moisture content is of special interest, since the intrinsic moisture content is hard to change (McKendry 2002). A possible drying (both natural and artificial) of biomass mainly reduces the extrinsic humidity; the intrinsic humidity is the limit up with the drying can go through. Drying of biomass is energy intensive, so if possible it should be avoided. Often the composition of biomass is pointed out without making any distinction between the two types of humidity, reporting only the total value.

The *fixed carbon* is the mass remaining after the release of all the volatiles, excluding the ash and moisture content. According to “EN 15148-2009 solid biofuels—determination of the content of volatile matter”, the volatile matter is the portion of released gas by heating of the solid biofuel to  $900 \pm 10$  °C for 7 min. *Volatile matter* is the fraction which volatilizes after heating (without any chemical attack). Being the reactivity of volatile gases much higher than the solid matrix, the quantity of free volatile matter (and the release velocity) is an important factor for the choice and dimensioning of thermos-chemical systems (pyrolysis, combustion, gasification). The fixed carbon together with the volatile matter is measure for the ease of ignition and further gasification or oxidation.

The fraction which still remains after having kept the biomass at a temperature of 900/950 °C for several minutes, is composed of *ashes* and “fixed carbon”. In other words, the ash content is the amount of solid residue left over when the biomass is completely combusted. The ash content affects both the handling and the processing costs of the overall biomass energy conversion (McKendry 2002). The analysis used in laboratory to determine humidity, volatile matter, fixed carbon and ashes is called proximate because it consists of the simply furnace heating in an inert atmosphere. Table 2.10 reports some examples of proximate analysis of biomass fuels, biomass residues and coals in terms of percentages of moisture, volatile matter (VM), fixed carbon (FC) and ash.

### 2.1.3.2 Elementary Composition

In the thermo-chemical processes typically adopted for the energy production from dry biomass (combustion, gasification, pyrolysis, liquefaction), the chemical-structural components described at Sect. 2.1.2, are separated and destroyed. The composition of the combustion (or gasification or pyrolysis) products and the mass and energy balances exclusively depend on the atomic species content of the fuel, that is, on its “ultimate composition”. In addition to the humidity, the biomass volatile matter is primarily composed by carbon, hydrogen

**Table 2.10** Typical proximate analysis of various biomass fuels, biomass residues and coals (De Jong and Van Ommen 2015)

Fuel	Proximate analysis (wt% as received a.r.)			
	Moisture	VM	FC	Ash
Wood pellets, clean	4.9	80.4	14.5	0.2
Wood pellets, demolition	9.1	69.6	19.7	1.7
Wheat straw	8.5	69.5	15.0	7.0
Sunflower pellets	11.2	65.2	19.5	4.1
Olive cake pellets	11.9	64.2	15.7	8.2
Pepper plant residue	6.5	60.5	19.5	13.5
Greenhouse residue	2.5	61.0	5.50	31.0
Sewage sludge, dried	8.7	47.2	4.7	39.4
MBM <sup>b</sup>	2.5	61.7	12.4	23.4
Microalgae	5.2	77.5	14.9	2.4
Macroalgae (seaweed)	8.0	42.4	19.5	30.1
Peat, (young surface), dry	12.5 <sup>a</sup>	63.1	22	2.4
Brown coal, dried	15.6	44.1	36.0	4.3
Bituminous coal	5.5	30.1	56.6	7.8
Anthracite	1.9	7.6	87.7	2.8

<sup>a</sup>Average value<sup>b</sup>Meat and bone meal

and oxygen with less content of nitrogen, sulphur and possibly, other elements such as sodium, potassium, chlorine, etc. Tables 2.11, 2.12 and 2.13 show some examples of ultimate composition of biomass and carbon and where available, their heating value.

With respect to the fossil fuels, biomass is characterized by:

- Less carbon content;
- Higher hydrogen and especially oxygen content;
- Significant less nitrogen and sulphur content;
- Less ashes content.

Coal contains between 75 and 90% carbon while biomass carbon content is about 50%. This means that the heating value of biomass is lower. Biomass fuels contain more volatile components and are more reactive than coal. These differences are explained by the O/C and H/C ratios of each fuel, shown in the Van Krevelen diagram.

Figure 2.1 shows according to the original Van Krevelen diagram, the variation ranges of oxygen and carbon in the volatile matter of biomass and the more common fossil fuels with their heating values calculated accordingly to Dulong–Berthelot equation (reported below).



**Table 2.11** Typical ultimate analysis of various biomass fuels, biomass residues and coals (De Jong and Van Ommen 2015)

Fuel	Ultimate analysis (wt% dry and ash free (d.a.f.))					
	C	H	O	N	S	Cl
Wood pellets, clean	45.6	6.6	47.8	BDL	BDL	BDL
Wood pellets, demolition	51.2	7.1	40.6	1.0	BDL	0.1
Wheat straw	47.3	5.5	45.3	0.9	0.5	0.5
Sunflower pellets	52.1	6.1	41.0	0.6	0.1	0.1
Olive cake pellets	52.7	6.3	38.9	1.6	0.1	0.4
Pepper plant residue	42.3	5.0	48.9	3.1	0.6	0.1
Greenhouse residue	70.8	11.1	16.4	1.5	BDL	0.2
Sewage sludge, dried	54.3	7.7	27.4	8.4	2.2	ND
MBM <sup>b</sup>	56.6	8.0	20.6	12.0	1.7	1.1
Microalgae	54.1	7.4	29.6	8.2	0.5	0.2
Macroalgae (seaweed)	41.1	7.5	46.2	5.2	6.3 <sup>a</sup>	21.7 <sup>a</sup>
Peat, (young surface), dry	52.6	5.8	40.6	0.9	0.1	0.0
Brown coal, dried	56.3	5.0	37.6	0.6	0.4	0.1
Bituminous coal	82.3	5.1	10.3	1.4	0.8	0.1
Anthracite	91.6	3.5	2.4	1.6	0.8	0.1

ND, not determined; BDL, below the lower detection limit

<sup>a</sup>wt% in dry ash (S and Cl contents can be high)

<sup>b</sup>Meat and bone Meal

**Table 2.12** Elementary composition and high heating value (HHV) of some substances (Vigouroux 2001). The HHV value in the right column is specific to kg of dry ash free matter, the other one is specific to dry matter kg, ash inclusive (Consonni 2006)

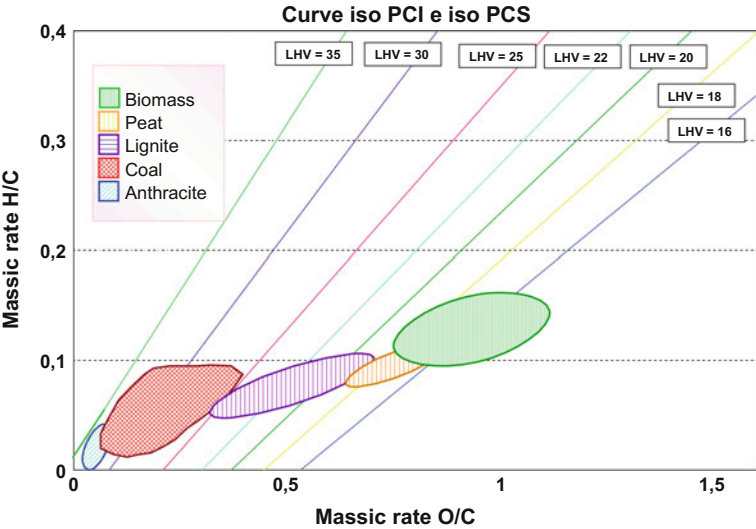
Biomass	%Moisture and a.f.			%mf			HHV		
	C	H	O	N	S	TOT	Ash	MJ/kg <sub>dm</sub>	MJ/kg <sub>daf</sub>
Birch	48.8	6.0	44.2	0.5	0.01	99.5	0.5	20.0	20.1
Poplar	49.8	5.9	44.4	0.6	0.04	100.7	1.9	18.3	18.7
Trembling poplar	48.8	6.0	44.7	0.5	0.01	100.0	0.5	20.0	20.1
Pine	49.3	6.0	44.2	0.5	0.01	100.0	0.5	20.1	20.2
Bark	47.2	5.6	46.9	0.3	0.07	100.1	3.9	20.9	21.7
Straw (Denmark)	49.6	6.2	43.6	0.6	n.a.	100.0	4.7	18.6	19.5
Miscanthus (Germany)	49.7	6.1	43.9	0.3	n.a.	100.0	2.3	18.4	18.8
Miscanthus (Italy)	49.5	6.2	43.7	0.6	n.a.	100.0	3.3	18.5	19.1
Sugar cane (Germany)	49.5	6.2	43.8	0.5	n.a.	100.0	3.7	18.5	19.2
Cane from Canarie	49.4	6.3	42.7	1.6	n.a.	100.0	8.8	18.8	20.6

n.a.: not analysed; dm: dry matter; daf: dry ash free; mf: moisture free

**Table 2.13** Ultimate analyses for typical biomass materials (wt%) (McKendry 2002)

Material	C	H	O	N	S	Ash	TOT
Cypress	55.0	6.5	38.1	–	–	0.4	100.0
Ash	49.7	6.9	43.0	–	–	0.3	99.9
Beech	51.6	6.3	41.4	–	–	–	99.3
Miscanthus	48.1	5.4	42.2	0.5	<0.1	2.8	99.0
Wheat straw	48.5	5.5	41.6 <sup>a</sup>	0.3	0.1	4.0	100.0
Barley straw	45.7	6.1	38.3	0.4	0.1	6.0	96.6
Rice straw	41.4	5.0	39.9	0.7	0.1	12.9 <sup>a</sup>	100.0
Bituminous coal	73.1	5.5	8.7	1.4	1.70	9.0	99.4

<sup>a</sup>100's complement of other elements percentage



**Fig. 2.1** Variation ranges of oxygen and carbon in the volatile matter of biomass and the more common fossil fuels. The LHV (MJ/kg) reported is dry and ash free and is calculated according to Dulong–Berthelot equation assuming nitrogen and sulphur content of 0.5 and 0.1%, respectively

2.1.4 Heating Value

The heating value of a fuel stands for the heat that can be released by its complete oxidation under standard conditions. Such a heat depends on the physical state of the water present in the combustion products, hence the distinction between high heating value (HHV) and low heating value (LHV). The first one corresponds to the complete condensation of water vapour in the combustion products; the second one to the case of water present as vapour in the products. Since this one is by far the most common case, in the devices used for energy production from biomass, LHV

should be the reference value. Obviously, an exception may be given to the technologies where water vapour is condensed (e.g. boilers running on natural gas) that is a rare case for appliances powered with biomass.

The heating value of dry matter of some biomass is reported in Table 2.12. Compared to the heating value of fossil fuels, the heating value of biomass is noticeably lower, mainly because of the huge presence of oxygenated bonds.

In practical applications, the main energy parameter is the heating value per kg of humid biomass; given the high moisture content typical of biomass, the heating value is generally significant lower than the one of the dry matter reported in Table 2.12. The discrepancy is higher for LHV than for HHV because, in order to have the water as vapour in the combustion products, a huge quantity of heating is necessary for the evaporation process.

Given the variety of biomass in terms of composition and physical state, experimental tests are needed in order to determine its heating value. HHV is experimentally determined using a so-called bomb calorimeter, a constant volume calorimeter, in which in a closed vessel a fuel portion is oxidized using pure oxygen. In this device, the heat transferred to a precisely known amount of water is measured by its temperature increase. The sample is ignited electrically. This is a standard method (e.g. DIN 51,900).

When these data are not available, empirical correlations based on ultimate analysis can give a first-attempt value. One of the most reliable is the Dulong–Berthelot equation:

$$\text{HHV} \left[ \frac{\text{kcal}}{\text{kg}_{\text{dvm}}} \right] = 8137 \cdot y_{\text{C}} + 34,500 \cdot \left( y_{\text{H}} - \frac{y_{\text{O}} + y_{\text{N}}}{8} \right) + 2250 \cdot y_{\text{S}} + 43.125 \quad (2.1)$$

where  $y_{\text{C}}$ ,  $y_{\text{H}}$ ,  $y_{\text{O}}$ ,  $y_{\text{N}}$  and  $y_{\text{S}}$  are, respectively, the mass fractions of carbon, hydrogen, oxygen, nitrogen and sulphur in the dry ash free matter (daf), expressed in kg of each atomic specie per kg of daf, or per kg of dry biomass ash free. Considering the relation between HHV and LHV, from Eq. (2.1), LHV is derived:

$$\text{LHV} = \text{HHV} - \left( \frac{W_{\text{H}_2\text{O}}}{2 \cdot W_{\text{H}}} \cdot y_{\text{H}} \right) \cdot \Delta h_{\text{ev}} = \text{HHV} - 9 \cdot y_{\text{H}} \cdot \Delta h_{\text{ev}} \quad (2.2)$$

where  $W_{\text{H}_2\text{O}}$  and  $W_{\text{H}}$  are, respectively, the molecular weight of water and hydrogen,  $y_{\text{H}}$  is always the hydrogen mass fraction ( $\text{kg}_{\text{H}}/\text{kg}_{\text{daf}}$ ) and  $\Delta h_{\text{ev}}$  the heat for water evaporation at standard conditions adopted for the LHV definition (at 25 °C,  $\Delta h_{\text{ev}} = 2.4425 \text{ MJ/kg}_{\text{H}_2\text{O}}$ ). Replacing in (2.2) and using the I.S. units:

$$\text{LHV} \left[ \frac{\text{MJ}}{\text{kg}_{\text{dvm}}} \right] = 34.061 \cdot y_{\text{C}} + 122.43 \cdot y_{\text{H}} - 18.052 \cdot (y_{\text{O}} + y_{\text{N}}) + 9.419 \cdot y_{\text{S}} + 180.52 \quad (2.3)$$

Based on this expression, the lines LHV-constant of Fig. 2.1 were plotted, assuming respectively for nitrogen and sulphur a concentration of 0.5 and 0.02%.

The heating value  $\text{LHV}_{\text{ar}}$  of the biomass as received is derived from the  $\text{LHV}_{\text{daf}}$  multiplying per  $\text{kg}_{\text{daf}}/\text{kg}_{\text{ar}}$ . Expressing the ash and moisture content as  $y_{\text{ash}}$  (kg ash/kg biomass as received) and  $y_{\text{m}}$  (kg  $\text{H}_2\text{O}$ /kg biomass as received):

$$\text{HHV}_{\text{ar}} = \text{HHV}_{\text{dvm}} \cdot (1 - y_{\text{ash}} - y_{\text{m}}) \quad (2.4)$$

$$\text{LHV}_{\text{ar}} = \text{LHV}_{\text{dvm}} \cdot (1 - y_{\text{ash}} - y_{\text{m}}) - y_{\text{m}} \cdot \Delta h_{\text{ev}} \quad (2.5)$$

Or, for LHV:

$$\frac{\text{LHV}_{\text{ar}}}{\text{LHV}_{\text{dvm}}} = (1 - y_{\text{ash}}) - y_{\text{m}} \cdot \left(1 + \frac{\Delta h_{\text{ev}}}{\text{LHV}_{\text{dvm}}}\right) \quad (2.6)$$

Being  $\Delta h_{\text{ev}}$  of about 2.45 MJ/kg $\text{H}_2\text{O}$  and the  $\text{LHV}_{\text{daf}}$  of woody biomass typically between 18 and 19 MJ/kg $_{\text{daf}}$ , their rate is about  $2/15 = 0.133$ .

In the systems where the combustion products are discharged as gaseous products (that is almost the entire thermochemical processes of any practical interest), the heat needed to evaporate the humidity implies a reduction of energy available in a quantity equal to:

$$\text{Fraction heat lost} = \frac{y_{\text{m}} \cdot \Delta h_{\text{ev}}}{\text{LHV}_{\text{dvm}} \cdot (1 - y_{\text{ash}} - y_{\text{m}})} \quad (2.7)$$

Figure 2.2 shows how the fraction of heat lost varies varying the humidity content. When the moisture is about 60%, the heat needed for the evaporation exceeds the available energy of more than 10%; for even higher values, the fraction of heat lost increases rapidly, reaching 100% when the humidity is about 90–95%.

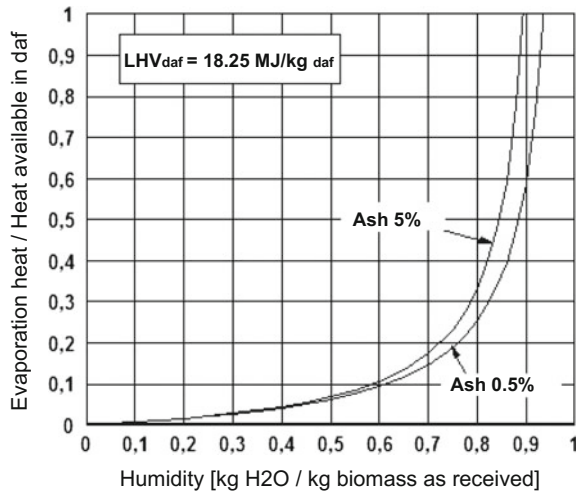
When the moisture content of biomass as received makes the LHV too low for any thermochemical process, biological processes are promoted.

## 2.2 Biomass Productivity and Energy Value

The production of biomass for energy purposes is simply a method to use the solar energy. As such, it is comparable to other kinds of use of the same source: photovoltaic, solar thermal, eolic energy and hydroelectric.

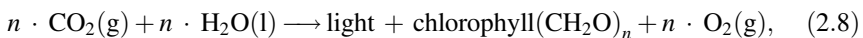
The use of solar energy through biomass may take different times, from some months for herbaceous plantations to some decades for plants to high stalk. Being these times comparable with the cycle of human activities, biomass represent a source of renewable energy, which can be indefinitely recollected until solar radiation and suitable climatic conditions will be available on our planet.

**Fig. 2.2** Heat lost for moisture evaporation depending on the moisture content in the biomass as received (Consonni 2006)



### 2.2.1 Chlorophyll Photosynthesis

The accumulation of chemical energy in biomass is the result of the complex chain of reactions defined as chlorophyll photosynthesis. The prime engine of such a mechanism is solar radiation especially the radiation visible with a wavelength within the range between 0.4 and 0.7 nm<sup>6</sup>. Photosynthesis develops in cellular organelles defined as chloroplasts by chlorophyll, the green pigment responsible for the capture of radiation and for a complex series of enzymes and catalysts like nitrogen, phosphorus, potassium and calcium. Among all compounds, ATP (adenosine-tri-phosphate) and ADP (adenosine-di-phosphate) assume an important role. The process has two steps, a dark phase and a bright one: such a definition does not relate to the presence of light, but simply to the role of solar irradiation, which is fundamental for the bright phase but irrelevant for the dark one. During the bright phase radiation promotes the formation of hydrogen ions and of free electrons, charging with energy the ATP derived from ADP; during the dark phase, ATP recovers the energy accumulated by returning to ADP status and promoting the synthesis of the bound (CH<sub>2</sub>O), which is itself the essential building block for the composition of carbohydrates (CH<sub>2</sub>O)<sub>n</sub> and C<sub>n</sub>(H<sub>2</sub>O)<sub>m</sub>. Overall, such a mechanism can be represented by the following equation:



where (g) and (l) specify the reagent physical state (both gas and liquid). At reference conditions of 25 °C, the energy stored in this process is about 470 MJ per mole of CO<sub>2</sub> converted in CH<sub>2</sub>O (Klass 1998).

The accumulation of chemical energy in the carbohydrates formed during chlorophyll photosynthesis resolves two main issues of renewable energies: the

intermittence of the source and the storage (Klass 1998). The chlorophyll photosynthesis is the way to convert solar energy in a chemical energy storage using a break-off process.

### 2.2.2 Efficiency

To synthesize  $\text{CO}_2$  in  $\text{CH}_2\text{O}$ , eight photons of solar radiation are needed. The maximum efficiency with which photosynthesis can occur has been estimated by several methods. The upper limit is the maximum amount of solar energy trapped as chemical energy in the biomass, that is 8–15% of energy content of the incident solar radiation (Klass 1998). A first method to estimate the photosynthesis efficiency is the rate between the chemical energy stored through (2.8) and the energy the photons need to promote this reaction. The relationship of the energy and frequency of a photon is given by:

$$e_f = h \cdot \frac{c}{\lambda}, \quad (2.9)$$

where

- $e_f$  energy content of one photon, J;
- $h$  Planck's constant,  $6.624 \times 10^{-34}$  J s;
- $c$  velocity of light,  $3.00 \times 10^8$  m/s;
- $\lambda$  wavelength of light

The eight photons absorbed during the reaction, have different wavelengths, thus, to correctly estimate their energy content, each photochemical elementary reaction should be considered (Twidell and Weir 2006). A first-attempt value for the total energy absorbed from the solar irradiation is given, assuming the same wavelength for all the photons and equal to 575 nm (the average value of the visible wavelength). The energy absorbed in the fixation of 1 mol  $\text{CO}_2$ , which requires eight photons per molecule, is then given by:

$$8 \left[ \frac{(6.624 \times 10^{-34} \text{ J s}) \cdot (3 \times 10^8 \text{ m/s})}{575 \times 10^{-9} \text{ m}} \right] \cdot 6.023 \times 10^{23} = 1665 \text{ kJ}, \quad (2.10)$$

where  $6.023 \times 10^{23}$  is the Avogadro number. Since 470 kJ of solar energy is trapped as chemical energy in this process, the maximum efficiency for total white light absorption is 28.2%. Further adjustments are usually made to take into account inefficiencies that can occur. Following Klass' path (Klass 1998), there are three main reasons of inefficiencies:

- The fraction of photosynthetically active radiation in solar radiation that reaches the earth is estimated to be about 43%. The energy of the visible radiation in fact, that is the number of photons with a wavelength between 400 and 700 nm, represents only part of the solar radiation energy whose spectrum spread along ultraviolet ( $\lambda < 400$  nm) and infrared ( $\lambda > 700$  nm) zone;

- The fraction of the incident light absorbed is a function of many factors such as leaf size, canopy shape and reflectance of the plant. It is estimated to have an upper limit of 80%;
- A portion of the stored energy is used by the plant, the amount of which depends on the properties of the particular biomass species and the environment. For purposes of calculation, Klass (1998) assumes that about 25% of the solar energy trapped as chemical energy is used by the plant, thereby resulting in an upper limit for retention of the no-respired energy of 75%.

From these considerations, the upper limit for the efficiency of photosynthetic fixation of biomass is as follows:

$$\text{Max capture efficiency} = \eta_{\max} = 0.282 \cdot 0.43 \cdot 0.80 \cdot 0.75 = 7.2\%$$

From this estimation, it is possible to calculate, depending on isolation, the upper productivity value in ideal conditions as:

$$P = \frac{\eta_{\max} \cdot I}{\text{HHV}_{\text{dvm}}}, \quad (2.11)$$

where

$P$	biomass produced ( $\text{kg}_{\text{daf}}/\text{m}^2 \text{ year}$ )
$I$	insolation
$\text{HHV}_{\text{daf}}$	High heating value of the dry ash free matter produced ( $\text{J}/\text{kg}_{\text{daf}}$ )

The use of HHV is coherent with the fact that the photosynthesis reaction goes with liquid water and the energy store refers to that physical state.

For example, at 45° Nord latitude (like Milan), the average annual insolation is more or less  $t$  4500 MJ/m<sup>2</sup> year (1250 kWh/m<sup>2</sup> year). Assuming a  $\text{HHV}_{\text{daf}}$  of 20 MJ/kg and ideal conditions in terms of isolation, weather, water and nutriment availability, the productivity will be around 16  $\text{kg}_{\text{daf}}/\text{m}^2 \text{ year}$ , or 160  $\text{tonn}_{\text{daf}}$  per hectare per year. As explained in the further paragraph, the real productivity is more than ten times less.

### 2.2.3 Production and Biomass Energy Yield

At real cultivation conditions, the capture yield of solar energy and the productivity are a lot less than the forecasted value. This is due to a lot of reasons:

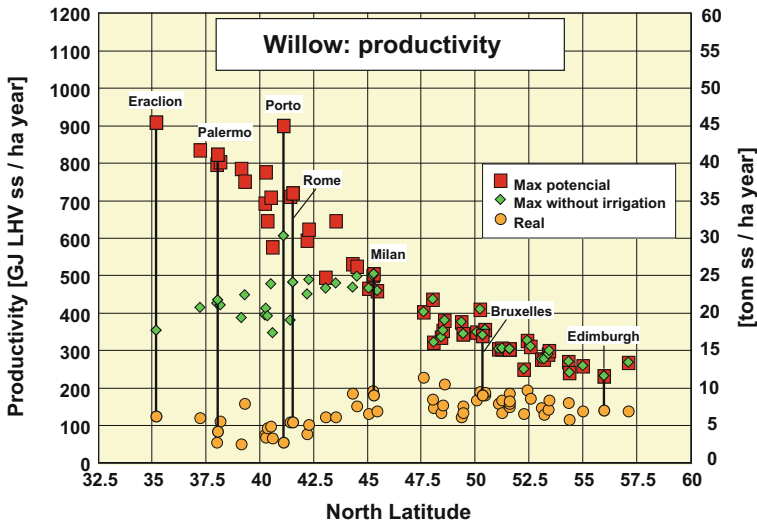
- The fraction of incident light really absorbed and used for the photosynthesis can be significantly lower than the values used for  $\eta_{\max}$  estimation;
- The capacity of completing the photosynthesis and producing storage matter strongly vary with the vegetal specie;

- For caduceus leaves species, the photosynthesis does not take place all the yearlong but only for a part of it;
- The real availability of water and nutriment limits the growing of vegetables organisms below the potential offered by the photosynthesis;
- Illness and parasitic limit the growth below the potential level.

A Dutch study realized by Nonhebel (Nonhebel 1997) for 58 European areas, shows the productivity of three interesting species used for energy production: the willow, the eucalyptus and the wheat. Willow and eucalyptus are interesting for energy production and wheat for food production. In Figs. 2.3, 2.4, and 2.5 the results are showed. We have three series of points, each one for a different growth condition:

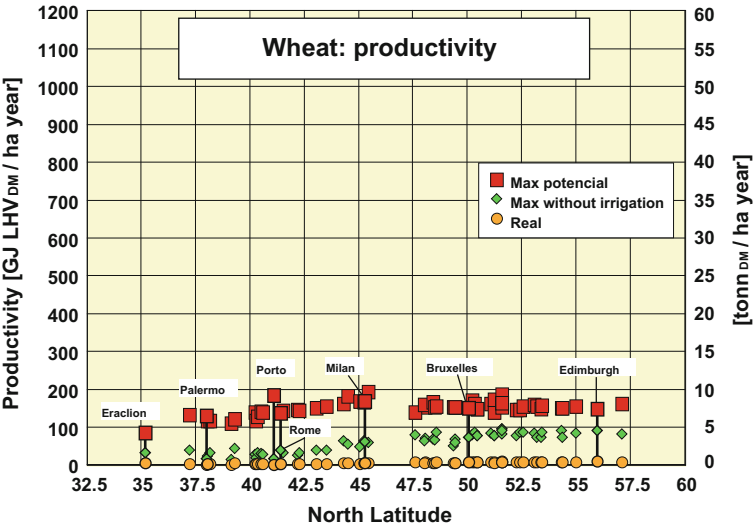
- The “real” series is the effective productivity in the European agricultural;
- The “max without irrigation” series shows the productivity in ideal condition of fertilizings supply and illnesses and parasites lack;
- The “max potential” series shows the productivity in ideal conditions of water availability and without illnesses or parasites.

Over a latitude of  $45^\circ$  the last two series coincide. This means that the water availability is a limiting factor only for the Southern European agriculture (like Portuguese, Italian, Greek and Spanish agriculture). We can also notice a huge

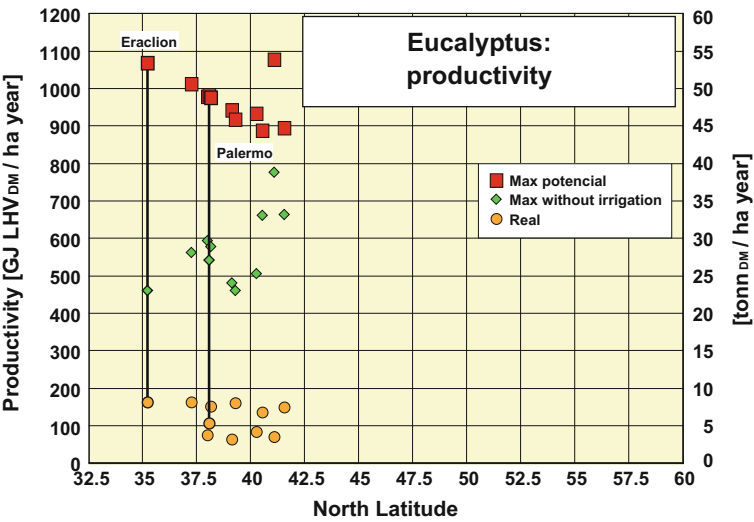


**Fig. 2.3** Willow productivity in (GJ of LHV<sub>ss</sub>/(ha-year)) and in (tonnes/(ha-year)) for different European areas at different latitude studied by Nonhebel (1997). For each 58 fields the figure shows the real productivity, the maximal one without irrigation and the best one. To avoid confusion, the figure represents only the name of some of the considered areas. The conversion between mass and energetic productivity is done assuming a LHV<sub>dm</sub> = 19.8 MJ/kg<sub>dm</sub> (Consonni 2006)





**Fig. 2.4** Wheat productivity in the same European areas already considered in Fig. 2.3. The conversion between mass and energetic productivity is done assuming a  $LHV_{dm} = 15.1 \text{ MJ/kg}_{dm}$  (Consonni 2006)



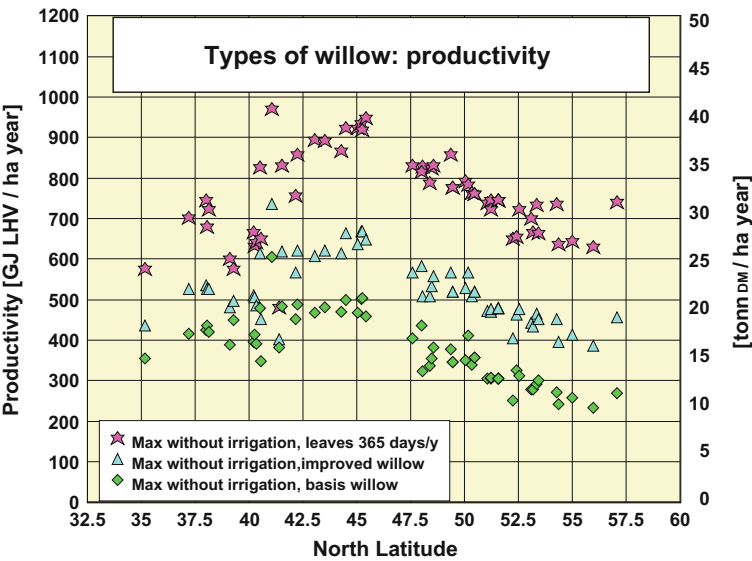
**Fig. 2.5** Eucalyptus productivity in the same European areas already considered in Fig. 2.3. The conversion between mass and energetic productivity is done assuming a  $LHV_{dm} = 18.1 \text{ MJ/kg}_{dm}$  (Consonni 2006)

difference between the potential and the real production that for the low latitudes can exceed one order of magnitude.

The comparison between the three productivities shows the difference between organisms “specialized” for food and for energy: the wheat productivity, that is its energy capture capacity, is only a few percent of the one of willow or eucalyptus.

Figure 2.6 quantifies the improvements obtainable with genetic changes of the willow. Even with a photosynthetic activity of 365 days per year, the willow productivity at 45° latitude will be no more than 45–50 ton<sub>dm</sub>/(ha year), less than one-third of the calculated value in ideal conditions (160 ton<sub>dm</sub>/(ha year)).

In Tables 2.14 and 2.15, we can find the productivity values of the oil and starchy plants founded in another recent study (EUROSTAT 2011). As we can see, for these cultures too, the gross productivity is some tens of GJ per ha per year.



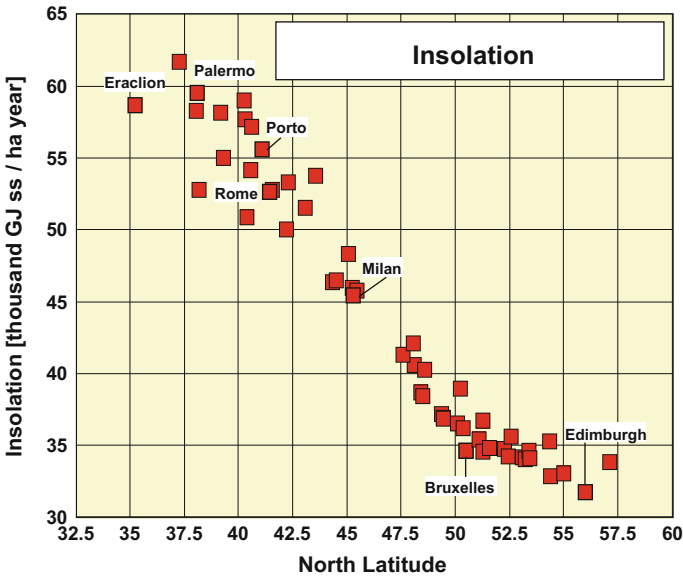
**Fig. 2.6** How a different type of willow can influence its productivity based on Nonhebel study (Consonni 2006)

**Table 2.14** Oil productivity from rapeseed. Sunflower and soya in Europe (EUROSTAT 2011)

Cultivation	Seeds productivity	Oil productivity		Oil specific energy	Energy oil content	Energetic input
	t/ha	% wt seeds	t/ha	MJ/kg	GJ/ha	GJ/ha
Rape	0.7–3.4	35–40%	0.3–1.4	37.4	11.2–52.3	13–37
Sunflower	0.5–2.5	40–48%	0.2–1.2	38.4	7.7–46.1	20–38
Soya	0.7–3.6	18–20%	0.1–0.7	36.4	3.6–25.5	15–35

**Table 2.15** Productivity of some amylaceous species and sugar species in Europe (EUROSTAT 2011)

	Wheat	Corn	Mais	Sorgho	Sugar beet
Charbohydrate (% in wt)	59–61	53–57	62–63	58–60	14–15
<i>Average productivity (t/ha)</i>					
Northern Europe	2.34	2.98	2.18	–	26.61
Central Europe	4.88	3.84	6.63	6.17	40.36
Southern Europe	2.77	2.77	4.88	5.70	41.13
<i>Average productivity (GJ/ha)</i>					
Northern Europe	22.7	26.5	21.5	–	62.3
Central Europe	47.3	34.1	65.3	58.8	94.4
Southern Europe	26.8	24.6	48.0	54.3	96.3



**Fig. 2.7** Average insolation in the areas already considered. The calculation was done with the procedure available on the website: <http://re.jrc.ec.europa.eu/pygis/solradframe.php?en&europ> (Consonni 2006)

The productivity values shown in Figs. 2.3–2.5 and the capture yields of the solar radiation shown in Figs. 2.8, 2.9 and 2.10 were calculated from the productivity and insolation values showed in Fig. 2.7.

Also for species, like willow and eucalyptus, strongly voted to the Energy production, the energy capture yields are very low, like 0.2–0.6% for willow and 0.2–0.4% for eucalyptus; if there is enough water and feed supply these yields can reach values of 0.8–1.5% and 2%, respectively.

## 2.2.4 Worldwide Productivity

The low values of yields showed in the previous paragraph, could bring mistrust in the contribution that the biomass source can give to the energy need of our society. Anyway, the diffusion of biomass is so widespread and pervasive that its potential can be more than enough to satisfy the world energy need.

The photosynthesis activity aims at fixing the CO<sub>2</sub>-carbon in carbohydrates. This is a key role for the greenhouse gases mitigation. Thus, the biomass production can be measured in terms of carbon fixed in the biomass organic material. Table 2.1 shows the world prospective. Every year, the photosynthetic activity fixes more or less 80 milliards tonne of carbon in organic matter. To highlight the renewability of the biomass source, the last right column shows the rate supply/production. That column means the time necessary to build again the existing biomass reserves. We can say that the biomass reserve can be built again in more or less 10 years; that time is of course longer for the ligneous biomass (22 years for forestry) and shorter for aquatic biomass (2–3 months). The cultivated lands are in the middle (1–2 years).

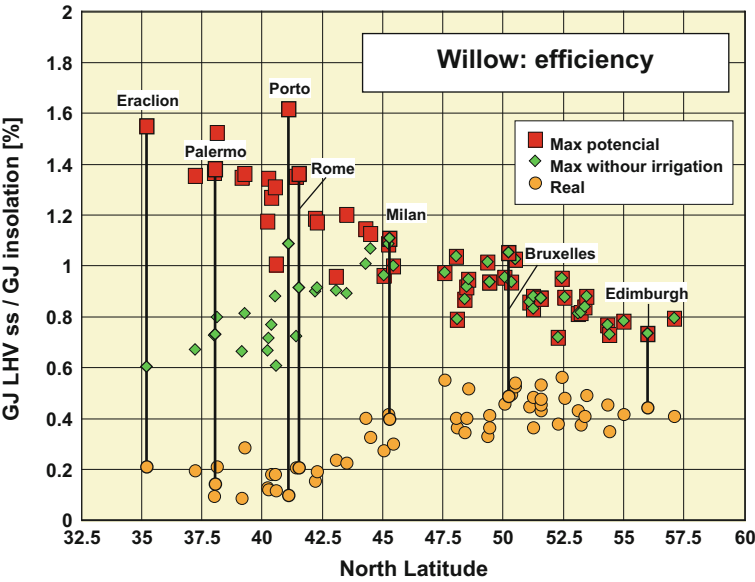
With an average carbon content in the dry ash free matter of 50%, to 80 Gton of carbon corresponds the production of 160 milliards tonne per year. For an average LHV of 15 MJ/kg<sub>daf</sub>, the content available in the biomass is more or less  $2.4 \times 10^{15}$  MJ, that is almost 57 milliards tonne oil equivalent (Tep) per year. This value is compared with the actual world consumption of energy of 13.5 milliards Tep per year (BP Statistical Review 2014).

The biomass source can theoretically cover the entire worldwide need.

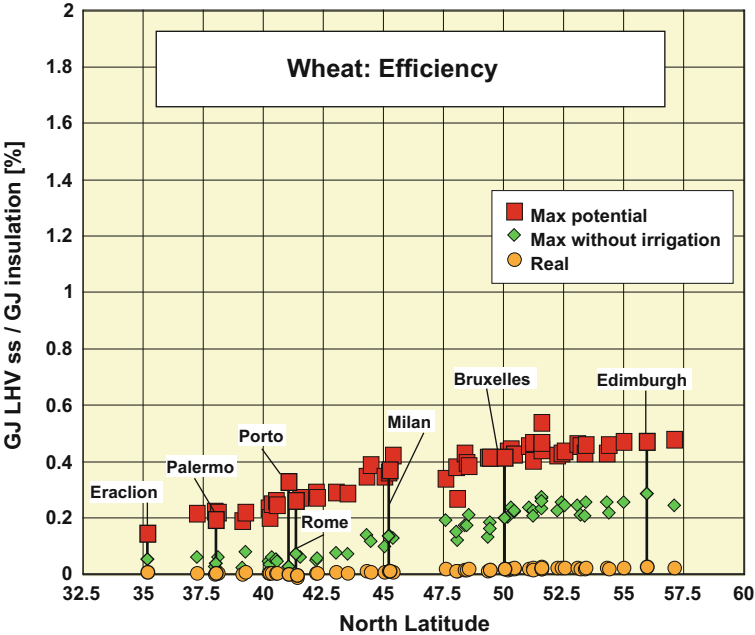
For a first-attempt estimation of the “terrestrial biomass system” yield, the biomass storage of energy in the terrestrial biomass can be compared with its annual insolation. Table 2.1 shows that the carbon production on the land area is about 67% of the total (52.9 milliard tonne/year over 79.1). According with the previous hypothesis, the corresponding energy storage will be about  $1.6 \times 10^{15}$  MJ/year. Of the approximately 1367.7 W (known as solar constant) per square metre that hits the earth’s atmosphere, considering the quantity that it has reflected away from the earth or absorbed by the atmosphere, clouds, etc., about 1 kW/m<sup>2</sup> is the radiation that invests an area perpendicular to solar rays. This power invests the section of our planet that can be considered as a circle of 6378 km radius. Follows:

$$1 \frac{\text{kW}}{\text{m}^2} \cdot \pi \cdot (6.378 \times 10^6 \text{ m})^2 \cdot \frac{8760 \text{ h}}{\text{year}} \cdot \frac{3600 \text{ s}}{\text{h}} = 4.03 \times 10^{18} \frac{\text{MJ}}{\text{year}}$$

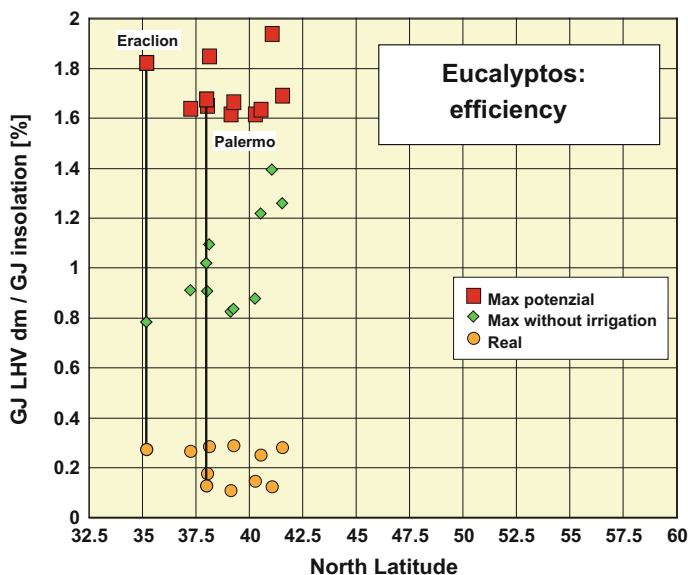
Assuming that this energy is split between sea and earth proportionally to their surface, the energy that reaches the 149 million km of land area, will be about  $1.15 \times 10^8$  MJ/year (149/520, see surfaces reported in Table 2.1). Following that the average yield of “biomass system” of land area is about 0.14% that is not so far from the “real” values shown in Figs. 2.8–2.10.



**Fig. 2.8** Average yield of the solar insolation capture of willow. The *points* in the diagram are the rate between the productivity and the insolation (Consonni 2006)



**Fig. 2.9** Average yield of the solar insolation capture of wheat. The *points* in the diagram are the rate between the productivity and the insolation (Consonni 2006)



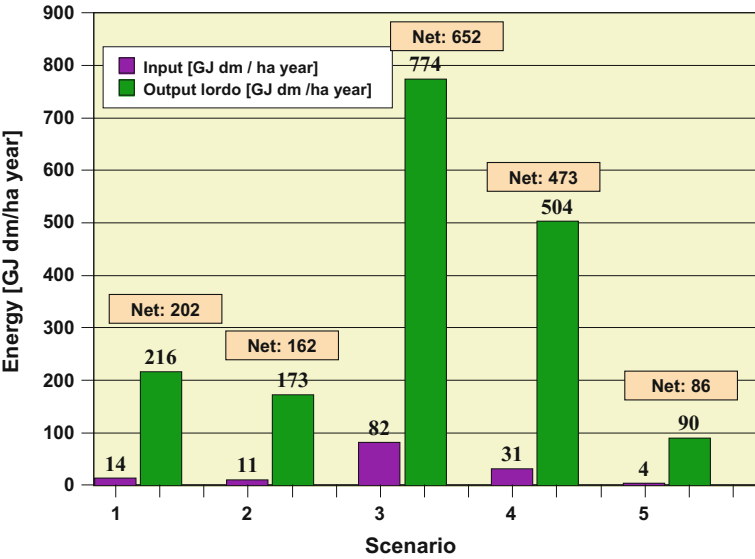
**Fig. 2.10** Average yield of the solar insolation capture of eucalyptos. The *points* in the diagram are the rate between the productivity and the insolation (Consonni 2006)

Apart from economic, technical or environmental considerations, the exploitation of the huge quantity of energy valued implies significant energy consumptions. This is why they wonder about the “energetic” convenience of biomass cultivation for energy purposes before the economic, environmental or social one.

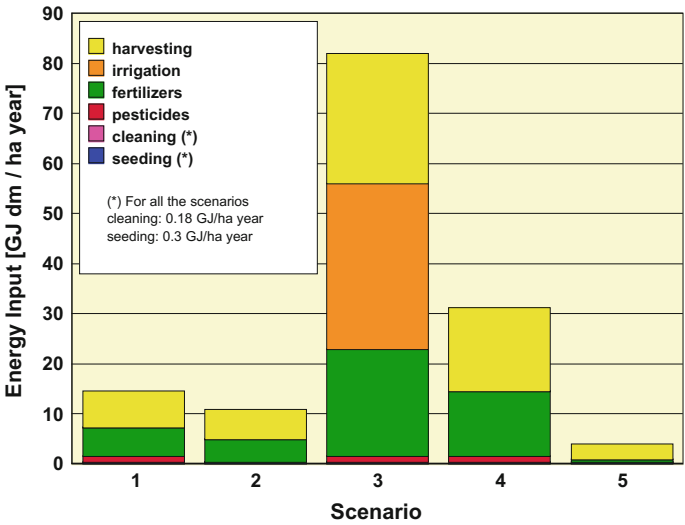
A positive answer to this question is given observing Figs. 2.11 and 2.12. That shows the energy balance for five different scenarios for the poplar cultivation for energetic purposes analysed by Nonhebel (Nonhebel 1997):

- Scenario 1: potential production feasible in north-western Europe, where we can obtain yields of almost 12  $\text{tonn}_{\text{daf}}/(\text{ha year})$ ;
- Scenario 2: the same condition of the Scenario 1 but without protection from parasitics and pathogen agents (reason of strong production reduction);
- Scenario 3: potential production feasible in the wonderful Portuguese climate where we can reach yields of 43  $\text{tonn}_{\text{dm}}/\text{ha year}$  with the use of irrigation and fertilizers;
- Scenario 4: the same of Scenario 3 but without irrigation;
- Scenario 5: short growth (5  $\text{tonn}_{\text{daf}}/(\text{ha year})$ ) experimented today in the south Europe.

Figure 2.11 shows that the energy balance for all the cultivations considered is positive even if the net output is different between the different cases. The rate between the energy produced (LHV of the dry matter) and the energy consumed varies between a minimum of 8.4 (Scenario 3) and a maximum of 22.1 (Scenario 5). The use of intensive techniques we have in Scenario 3, particularly the irrigation,



**Fig. 2.11** Energetic input and output [ $\text{GJ}_{\text{dm}}/(\text{ha year})$ ] for five scenarios of poplar cultivation studied by Nonhebel (1997). The gross output is the product between the dry matter [ $\text{tonn}_{\text{dm}}/(\text{ha year})$ ] and its LHV<sub>dm</sub> (18 MJ/kg<sub>dm</sub>) (Consonni 2006)



**Fig. 2.12** Detailed energy input for the scenarios previous analysed (Consonni 2006)

**Table 2.16** Productivity range for annual (A) and poliannual (P) coltures (EUROSTAT 2011). For Energy ratio we intend the rate between energy out and energy in (EUROSTAT 2011)

	Productivity (t <sub>ss</sub> /ha)	Specific energy (GJ/t)	Output (GJ/ha)	Input (GJ/ha)	Energy ratio	Output-input (GJ/ha)
Sorgho fibre (A)	20–30	16.7–16.9	334–507	13–25	13–39	309–494
Sorgho sugar (A)	15–25	16.7–16.9	250–422	13–25	10–32	225–409
Kenaf (A)	10–20	15.5–16.3	155–326	13–25	6–25	130–313
Hemp (A)	8–15	16.0–18.0	128–270	13–25	5–20	103–257
Mischantus (P)	15–30	17.6–17.7	260–530	8–22	12–66	238–522
Sugar cane (P)	15–35	16.5–17.4	240–600	8–22	11–75	118–592
Thistle (P)	10–15	15.5–16.8	155–252	8–22	7–31	133–244
Panic grass (P)	10–25	17.4	174–435	8–22	8–54	152–427

increases a lot the productivity but reduces the “efficiency” of the operation that is the rate between the produced energy and the consumed one. The Scenario 5, representative of the warm countries in Southern Europe (Italy, Spain, Greece), has the lowest productivity but the highest “efficiency”.

In Table 2.16, we have the net productivity values for some herbaceous species.

Finally, at our latitudes, the potential for the energy production, in the best conditions, can reach the 500–600 GJ/ha/year. Anyway, in the real conditions, the production can also be a lot lower than 100 GJ/ha/year.

### 2.2.5 Limitations of Energy Production from Biomass

Previous paragraphs show that the minor role played nowadays by biomass in energy production, it is not due to an insufficient potential production but to a series of historical, technical, economic, environmental and social reasons. The most relevant are as follows:

- The agriculture production is fairly oriented to food production rather than energy. The conversion of relevant areas to energy cultivations is a problem from the alimantal/energy aims competition point of view;
- The major part of the areas with high biomass production potential (forests, woods, savannas, grasslands) is high environmental-biological and landscape value ecosystems. Their conversion to energy cultivations sets difficult problems related to ecosystem protection and social/political acceptance;
- A consistent part of biomass production reported in Table 2.1 takes place in remote and impassable places, where the intensive exploitation of mineral resources for energy purposes would be difficult and expensive;



- Biomass is an energy source more difficult and expensive than fossil fuels;
- The production efficiencies of electricity, heat and fuels from biomass are typically lower than the ones from fossil fuels;
- Technologies and systems required for biomass collect and transport are typically more complex and expensive than the ones required by fossil fuels;
- Technologies and systems adopted for the generation of energy vectors from biomass are more expensive and difficult to manage than the ones adopted for fossil fuels;
- The biomass exploitation for energy purposes can show serious problems from an environmental point of view, sometimes more difficult to solve than the ones presented by the exploitation of fossil fuels. The only exception is for the greenhouse gases emissions, almost null;
- A wide diffusion of energy cultivations would require a significant change in habits of people that act within the agriculture sector.

All these reasons are not listed to discourage the use of biomass for energy aims but simply to make aware of the problems that have to be solved.

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