Biomass

Introduction

In 2012 biomasses satisfied approximately 10% of energy requirement worldwide (*International Energy Agency Key World Energy Statistics 2014*). Exploitation of this resource is not distributed homogeneously across the Planet. The vegetation that covers our planet is a natural storage of solar energy. The organic matter composing it is called biomass. Biomass is produced through the photosynthesis process, when carbon dioxide from the atmosphere combines with underground water to produce sugars, starch, cellulose, lignin, protein substances, fats, etc. The same solar energy that activated the photosynthesis is contained in the chemical bonds of these substances. In this way 2×10^{11} tons of carbon are fixed each year, with a corresponding energy content of 70×10^{3} megatons of oil.

Biomass knowledge

What is it?

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By burning biomass, atmospheric oxygen combines with the carbon contained in the biomass, freeing carbon dioxide and water, and producing heat. Carbon dioxide goes back into the atmosphere and is ready to be re-used in the photosynthesis process to produce new biomass. Therefore biomass is a renewable resource.
The term biomass indicates several types of products: agricultural and forest residues, waste of wood processing industry (wood shavings, sawdust, etc.), waste of the zoo-technical industry, agricultural and food residues (residues of crops for the production of human and animal food (straw), “energy cultures” aimed at the production of fuel, and organic biomass from other sources, such as the green fraction of solid urban waste and other types of heterogeneous industrial waste.

What is for?

In The main applications of biomass are: energy production (biopower), fuel synthesis (biofuel) and product synthesis (bioproduct).
In the energy field, wood and cellulose biomass (wood and by-products of grass, tree and forest cultivation) is mainly used as multi-purpose fuel: household heating, to produce electric energy and industrial uses.
Other sectors affected by the processing of this raw material are: the sectors of paper, cellulose, particle-board, compounds, animal food and chemical products.
“Energy culture”, i.e. the cultivation of vegetal species growing rapidly, are generally used in the production of bio-fuels. For example, the processing of organic matter of plants producing vegetal oil and sugars (sunflower, sugar sorghum and beetroot) are the raw material of bio-ethanol, which can be used as an additive for petrol and bio-diesel, that is a mixture similar to gas-oil.
Bio-fuels, as well as producing heat and/or electric power, can be used as a car propeller, both mixed with other fuels or pure.

Where is it?

Biomass is one of the most abundant renewable energy sources on our planet. In 2015, biomass covered 9.7% of world energy requirements (*International Energy Agency Key World Energy Statistics 2017*). Its use, however, is not evenly spread. Bioenergy plays a role in all three main energy-use sectors: heat (and cooling), electricity and transport.

Biomass in many forms - as solids, liquids or gases - can be burned directly to produce heat for cooking and heating in the residential sector by means of the traditional use of biomass or in modern appliances. It also can be used at a larger scale to heat larger institutional and commercial buildings, or in industry. The traditional use of biomass for heat involves primarily the use of simple and inefficient devices to burn woody biomass, in the form of fuelwood or charcoal, or agricultural residues and dung burned. Biomass energy use in 2016 is estimated at 46.4 EJ (1 exajoule (EJ) is equal to 10^{18} joules), although it is difficult to quantify the volume consumed given the informal nature of the supply and uncertainty regarding the use of these biomass materials.

Traditional biomass is mainly used in developing countries, where this energy source represents 34% - 40% of the total energy requirement. Modern bioenergy applications, on the other hand, are primarily used in developed countries, like Europe, Asia and North America.

Bio-power capacity increased by an estimated 7% in 2017, to 122 GW, and generation rose by 11% to 555 TWh. The leading countries for electricity generation from biomass in 2017 were China (79.4%, the United States (69 TWh), Brazil (49 TWh), Japan (37 TWh) and India (32.5 TWh). In Italy, on the other hand, in 2016 19.5 TWh of electricity were produced from biomass: the biomass contribution domestic electricity production was therefore 5.7%.

Finally, the global production of biofuels increased by 2.5% in 2017, reaching the record value of 143 billion litres produced. Ethanol fuel accounted for 65% of the total, biodiesel for 29% and hydrogenated vegetable oil (HVO) for the remaining 6%. Global production of biofuels was dominated by the United States and Brazil, followed by Germany, Argentina, China and Indonesia.

(Data source: Renewables 2018, Global Status Report)

A bit of history

Fire, unquestionably the most important discovery in the history of mankind, was discovered thanks to the accidental combustion of wood. Fire has illuminated, heated, protected and fed mankind for thousands of years. Briefly, fired fostered the birth of civilisation.

Wood, on the other hand, remained the most widely used raw material for many centuries, not only to burn fires, but also as building material. The invention of the steam engine allowed mankind to obtain mechanic energy from the combustion of wood, whereas up to the 18th century wind and water where the only mechanic energy sources available, thanks to wind and water mills.

During the Industrial Revolution wood started to become scarce owing to the massive deforestation carried out to produce energy. Mankind had to look for alternative energy sources and found them in coal and oil, which at the time were abundant albeit not renewable.

Only recently, energy need and the possible disappearance of fossil fuels and the pollution produced by the combustion led man to “re-discover” the usefulness of wood and biomass as energy sources.

Biochemical processes

Biochemical processes work thanks to the action of fungi and bacteria that grow in the biomass in specific conditions of temperature and humidity. These micro-organisms digest organic matter freeing molecules that are waste (for them) but precious for us. Not all biomasses are suitable for these processes: fungi and bacteria do not eat absolutely everything but necessitate organic matter rich in proteins and water. Seaweeds, rejects from the cultivation of potatoes and beets, food waste and animal faeces are very good.

The main products that can be obtained with these methods are biogas, bioethanol, fertilizers for agriculture and heat. Biogas is a mixture of gases, predominantly methane (50-70%) and carbon dioxide, which can be used for heating purposes or to make some particular plants allocated to the production of electrical energy work.

Bioethanol is an alcohol that can be used as car fuel. It is obtained from the fermentation of the sugars of beets and sugar cane. It is a fuel of great interest because it is clean and cheap. It has been calculated that 11 million tonnes of bioethanol are produced annually, especially in U.S.A. and Brazil.
Another interesting application of biomass is for heating animal farms and cultivations. The decomposition of waste products, like leaves or animal faeces, produce heat that can be used to warm up greenhouses and stables.

Thermochemical processes

It is well known that to light and feed a fire you need materials that burn and these, in technical terms, are known as fuel. Fuel alone is not enough for a fire to burn, another element is required: the combustive agent. The most common combustive agent is oxygen, which, in a combustion reaction, has the task of “oxidizing” the fuel, with the consequent release of energy in the form of heat and light. Fire therefore is simply the visible manifestation of a chemical reaction, combustion, that takes place between two different substances: the fuel and the combustive agent. There are numerous combustible substances and materials. Initially man burnt wood, then coal. Today the most common fuels are the fossil fuels: petroleum, methane gas and coal or fossilized carbon.
Combustion is the most ancient method to obtain energy from the biomass. Antique fireplaces, chimneys and stoves have now been replaced by modern and efficient heaters that are able to exploit the hidden energy of wood and its derivatives. Fungi and bacteria prefer humid protein substances, but fire feeds best on dry materials that are rich in cellulose. Cellulose is a complex molecule. It is very resistant and consists of long glucose chains, the most simple of sugars. Plants are made of cellulose, so are wood, leaves, paper and cotton. There are various systems to obtain energy from wood, that are classified according to the combustion temperature and the type of physical and chemical transformation that is obtained. Firstly it must be pointed out that these systems use crushed wood. The chips of wood can be used just as they are, or compacted in small blocks or pellets. Wood pellets increase the efficiency of the heaters and leave them cleaner. Wood transformed in this way can be burnt at extremely high temperatures (about 1000°C), and it turns into a mixture of gases that can move turbines and produce electric power. When it is burnt at lower temperatures, (from 400 to 800°C) wood separates into gases, liquids and solids. The solid component, coal, can still be used as a fuel, and the liquid component, pyrolysis oil can be used as a fuel for engines or can be used as the base in the synthesis of other products.

Energy production

Biopower

The technologies used to obtain energy (biopower) from different types of biomass are different and the resulting energy products are different too.
Biopower technologies convert renewable fuels of biomass into heat and electricity by using equipment, which is similar to the one used for fossil fuels.
An advantageous characteristic of biomass is its availability, as it is able to keep its energy intact until it is used.
Briefly, thermo-chemical conversion processes of biomass are based on the action of heat that activates the chemical reactions needed to transform the matter into energy and can be used for those cellulose and wood residues whose C/N ratio is over 30 and the humidity content is lower than 30%.
The biomass that is more suitable to be subject to thermo-chemical conversion are wood and all its derivates (sawdust, wood shavings, etc), the most common wood-cellulose by-products (cereal straw, grapevine pruning residues, fruit trees pruning residues, etc) and some processing waste (husks, chaff, stones, etc).
Bio-chemical processes: bio-chemical conversion processes allow to obtain energy throughout a chemical reaction that takes place thanks to the contribution of enzymes, mushrooms and micro-organisms, that form in the biomass under particular conditions, and are used for that biomass whose carbon/nitrogen ratio is lower than 30 and humidity at collection is higher than 30%. The following products are appropriate for chemical conversion: aquatic breeding, some cultivation by-products (leaves, sugar-beet stems, vegetables, potatoes, etc.), liquid residues of zoo-technical industry

and some processing waste (residues of alcohol processing made of grains, vegetation water, etc.), and some types of urban and industrial waste water.
The technologies that are currently used in the biopower sector are: cofiring, pyrolisis, gasification, combustion, “small modular” systems, aerobic digestion, anaerobic digestion, and carbonization.

Gasification

At present, in terms of biomass, “gasification”, which is a thermo-chemical process, is considered as one of the best and most promising technologies to produce electric energy: both as far as efficiency and environmental impact are concerned.
Each plant is subdivided into three sections, where three stages of the productive process are carried out: gasification, gas turbine and thermal cycle. During gasification, the wet biomass is conveyed into a drier making excess water evaporate. After being dried, biomass proceeds to the gasifier, where it is transformed in a synthetic gas composed of molecular nitrogen (N_2), steam (H_2O), carbon monoxide (CO), carbon dioxide (C_2), molecular hydrogen (H_2), methane (CH_4) and a small fraction of heavier hydrocarbons.
Then the synthetic gas is cooled and filtered to eliminate dust, contaminants (cyanic acid, ammonia and hydrogen chloride) and organic compounds (phenols and fatty acids).
After being compressed, it is ready to operate the gas turbine where it will be burnt to heat the air to be conveyed to the thermal cycle. In the last section of the plant a boiler recovers the heat contained in the air coming from the gas turbine and produces steam for another turbine, which will operate the electric current generator.

Cofing

In order to optimise coal plants, it is possible to use biomass as complementary to coal. This is surely one of the cheapest solutions among the energy options offered by renewable sources. The cofiring is based on the replacement of a portion of coal with biomass to be used in the same boiler located in the already existing plant. This can be done by mixing biomass with coal before the fuel is introduced into the boiler or using separate feeding systems for coal and biomass. According to the type of boiler and the feeding system used, the biomass can replace up to 15% of coal in this cofiring operation.

Pyrolysis

Pyrolysis is the thermo-chemical decomposition of organic materials that is obtained through heat application, at a temperature between 400 and 800°C, in complete absence of any oxidizing agents, or with a very reduced quantity of oxygen (in this case it can be described as a partial gasification). The products of pyrolysis can be gaseous, liquid, solid and their proportions depend on the pyrolysis method (fast, slow or conventional) and reaction parameters. One of the main problems linked to the production of energy through pyrolysis is the quality of the products, which has not reached an adequate level in its applications, neither with gas turbines nor diesel engines. For the future, the cycles with pyrolytic oil seem to be more promising, especially for large installations, while diesel engines, that use pyrolysis products, seem to be more suitable for small installations.
Direct combustion generally occurs inside equipment (boilers), where the heat is exchanged between combustion gases and process fluids (water, etc.).

Combustion

The combustion of products and agricultural residues has good results if substances rich in structured glucides (cellulose and lignin) and with a water content of less than 35% are used as fuels. The products that can be used are the following: wood in all its forms, cereal straws, residues of dry legumes, residues of oleaginous plants (castor-oil plant, etc.), residues of textile fibre plants (cotton, hemp, etc), wooden residues deriving from the pruning of fruit and forest plants, residues of the agro-food industry.

"Small-modular" systems

These systems could potentially satisfy the energy need of 2.5 billion people that have no electric energy. This capacity is due to the fact that most of these people live in areas where large quantities of biomass can be used as fuel. A small system with a capacity of 5 megawatts could be an excellent solution in villages. Small systems have a potential market also in industrialized countries, as they could be used as a complementary energy supply. Compared to fossil fuel systems, they are a more acceptable alternative also from the environmental point of view.

Carbonization

Carbonization is a thermo-chemical process that allows to transform structured molecules of wood and cellulose products into coal (wood coal or vegetal coal). Carbonization is obtained through the elimination of water and volatile substances from the vegetal matter, due to the action of heat in charcoal pile (cone-shaped wood piles, covered with earth, with a central outlet channel (chimney), where a slow wood combustion takes place, turning the wood into coal). Carbonization occurs outdoors, or in long and curved-neck containers, with a flask shape, that offer a higher coal yield.

Anaerobic digestion

It is a biochemical conversion process that occurs in the absence of oxygen and consists of the demolition, by micro-organisms, of complex organic substances (lipids, proteins, glucides) contained in vegetal and animal by-products, which produces a gas (biogas) made of methane (50-70%) and the rest is mainly CO2 and has an average calorific value of 23,000 kilojoules per cubic metre. The resulting biogas is collected, dried, compressed and stored, and can be used as a fuel to feed gas boilers and produce heat (also coupled with turbines for the production of electric energy), or to feed combined-cycle plants, or internal combustion motors (boat engines with a low number of turns are suitable for this). At the end of the effluent fermentation process the main nutritional elements that were already present in the raw material are kept intact (nitrogen, phosphorus, potassium), by favouring the mineralization of organic nitrogen. The effluent results to be an excellent fertilizer. Anaerobic digestion plants can be fed through residues with a high humidity content, like animal faeces, civil waste (waste water), food waste and the organic fraction of urban solid waste.
However, also in those dumps that are suitably equipped for the collection of biogas, only 40% of the gas produced can be collected, while the remaining part is dispersed into the atmosphere. As the methane, that largely composes biogas, is a greenhouse gas with an effect that is twenty times as high as CO2 , emissions of biogas into the atmosphere are not desirable. When the decomposition of organic waste is obtained through anaerobic digestion of (closed) adequate plant digestors, almost all the gas is collected and used as a fuel.
The recovery of the biogas from dumps is a system that has been experimentally adopted in various countries (England has developed an efficient system of biogas recovery from dumps, both for thermal and electric aims).
In Sweden, there are biogas refuelling stations that supply methane vehicles.

Aerobic digestion

It is the metabolization of organic substances through micro-organisms, whose development depends on the presence of oxygen. These bacteria convert complex substances into simple ones, releasing CO2 and H2O and highly warming up the substrate, according to their methabolic activity. The resulting heat can then be trasferred outside, through fluid heat exchangers. In Europe the aerobic digestion system is used to treat waste waters. More recently, this technology has spread to Canada and the United States.

Biomass plants

Biomass district-heating

A district heating system consists of a transport network and a heat production plant, which serves more than one building at the same time. The district heating plant can use co-generation technologies and/or renewable sources.

The installations

The heat that is distributed by urban district heating systems derives from simple production installations (only heat) and combined production installations (heat + electric energy).

The first type of installations includes boilers for the production of heat as vapour, hot water, superheated water, oil. Combined production installations, instead, are co-generation plants that in today practice can be fed by a vapour cycle with internal combustion motors, gas turbines, with a combined cycle.

The distribution network is the most expensive part of the district heating plant: its cost should amount to 50-80% of the total investment. The distribution system can use different types of fluids: the trend in Italy is to use hot water (80-90°C), or slightly superheated (110-120°C).

Heat distribution

The distribution system can be direct or indirect. In the first case, a single hydraulic circuit connects the production plant with the user's heating body (radiator or plate). In the second case, there are two separate circuits that are in contact through a heat exchanger. The direct system requires a lower investment and causes fewer heat losses.

District heating: an excellent solution

The excellent solution to exploit biomass, as well as the use of individual heating in pellet boilers (wooden balls) or nipper boilers, is the district heating with small-sized biomasses (10 megawatts), that supplies heat to households and/or business activities, and is located close to the biomass production site (wood, farm land, sawmill, etc). If the biomass is produced locally, the dimension of the plant has to be carefully decided, in order to allow sources to regenerate. Sizes bigger than 10-15 megawatts force to excessively increase the supply, therefore increasing economic and environmental costs of transports on the one hand, and going at the disadvantage of the wood sector (production, processing and the sale of products) on the other hand. In Austria small rural district heating plants with biomass are more than 300, with a power included between hundreds of kilowatts and 8 megawatts. In Italy, instead, plants are only a few tens, although the sector seems to be very vital. One of the main reasons for the success of these plants is Austria is linked to the fact that the agricultural economy concentrates on forest activities. There is also a reduction in the wood demand; this led to a price drop and provoked problems to the agricultural sector, forcing to find a solution that could allow prices to go up to an acceptable level for local producers.

The majority of district heating plants was created in rural and economically depressed areas, but also many tourist sites have devoted attention to this technology, based on very low emissions. They saw this renewable source as an element for tourist promotion. Also in Italy these plants could be the answer to the depression of some areas, with the creation of new jobs for the maintenance of forests (economically and environmentally convenient activity), and the prevention of erosion, landslides, floods and fires. Biomass district heating is to be considered as a complementary technology, not be seen as an antagonist of domestic biomass boilers. District heating installations, with grill boilers, can burn all types of wood waste, although it is very wet and with a low calorific value.

Household wood boilers, instead, cannot use these types of waste. They burn dry and quality wood, of adequate size, or it is necessary to opt for pellet boilers in order to automatize the installation, avoiding to have to supply it continuously (even several times a day in winter). This wood, in fact, occupies less room with the same quantity of dry mass being burnt, guarantees a more regular combustion and a simpler transport/storage. This variability in the supply system of biomass installations allows to exploit all the products deriving from wood maintenance: the waste (branches, barks, roots, etc. also very wet) is used for district heating if there is an adequate number of users, while dry trunks and pelletized waste for isolated households. The residues (of wood cleaning, agricultural farming, sawmills, etc), without a biomass-supplied installation, would be disposed of in a different way: if they were left in the air they would produce the same quantity of CO_2 as was stocked during their growth. If fermentation occurred in the absence of oxygen, methane would be produced, whose contribution as a greenhouse gas is 21 times (in terms of weight) as high as the weight of CO_2. If these residues are disposed of in factories (paper mills, etc), they often impose quite high transport costs (environmental and economic ones). In order to plan the construction of a biomass district heating installation, it is necessary to satisfy the following pre-requisites:

- the distance from the supply site cannot be too big, as the transport can significantly affect the cost of the raw material (and the quantity of CO_2 released by the installation)
- the closeness to the supply source can allow to have a smaller storage volume inside the district-heating plant (allowing to build it also in narrow areas), having the chance to do the storage at the supplier's place
- it is necessary to have an adequate area, close to the transport network and conveniently close to the households, where the installation and the storage warehouses will be built, without having too many problems due to the traffic.

Biofuels

Biofuel production

The word biofuel may refer to the fuels used for the production of electric energy, but in general it refers to liquid fuels used for means of transport.
The most common fuels are undoubtedly bioethanol synthetized from carbohydrates and biodiesel (ester) obtained from fats and oils. Although ethanol obtained from starch and sugars, it offers a good contribution from the energy and environment point of view. Later we will examine ethanol produced from cellulose biomass like herbaceous and wooden plants, agricultural and forest residues and large quantities of urban and industrial waste.
In fact, while starch and sugars represent a modest quantity of plant material, cellulose and hemicellulose, which are polymers of sugar molecules, represent most of the biomass. The benefits connected to biofuels derive from the fact that they have a more limited environmental impact than oil derivatives and use waste materials that are usually not employed. Finally, other two biofuels will be analysed, that is methanol and corrected petrol compounds.

Bioethanol

Ethanol has always been used for internal combustion engines, as demonstrated by the history of cars. But, although the initial large availability and the low cost of hydrocarbons had not allowed to use them as fuels, after the oil shock of 1973 many other products were studied to replace car fuel (petrol and gas oil). Today, the product that shows a better compromise between price, availability and performance is ethanol.
The synthesis of biomass ethanol is divided into four stages:

- production of biomass by fixing atmospheric CO_2 into organic carbon
- conversion of biomass into a food that can be used for fermentation (usually as a sugar), by applying one of the many technological processes available: this conversion is what mainly differs with the various technological solutions for bioethanol conversion
- fermentation of biomass intermediates by using bio-catalizers (micro-organisms like yeast and bacteria) in order to obtain a scarcely concentrated solution of ethanol. This stage can be considered as the oldest biotechnology ever developed by men
- by processing the fermentation product the result is: combustible ethanol and by-products that can be used to produce other fuels, chemical compounds, heat and electric energy.

All these last processes, even though they are very different, conclude with the fermentation synthesis. The alcohol fermentation is a process that transforms the glucides contained in vegetal productions into ethanol.

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Biodiesel

Recycled vegetal oils, animal fats and kitchen fats can be transformed into biodiesel by using a series of technologies in order to activate those chemical reactions, at low temperatures, that lead to the formation of compounds called esters. Esters can be liquid or solid; they are soluble in organic solvents and have a pleasant smell. Then they are transformed into biodiesel and glycerine. Glycerine is a secondary product that can be used for the production of hand creams, toothpaste and lubricants. Biodiesel can be directly used, since it does not require any type of intervention on the systems that apply it (motors and burners). It is used for motor propulsion (diesel engines) both as pure and mixed with the common gas oil and for heating.

The use of biodiesel reduces the energy dependence on fossil fuels, the greenhouse gases emissions and health risks due to air pollution. It is not toxic and it is biodegradable within 30 days. Diesel mixed with biodiesel has a triple biodegradability.

Biodiesel contains traces of sulphur, that are in line with the new parameters established by EPA (Environmental Protection Agency) and that will be applied from the year 2006.

It is safe to be handled and transported: it can be stored in the same tanks as the diesel and pumped with the same equipment, except when it is cold (it is necessary to use tank heaters or shakers). It can be completely mixed with diesel and for this reason it is a very flexible additive.

Biodiesel, since it is an oxygenated product, helps to complete combustion. The reduction of polluting emissions is proportionate to its concentration in mixtures. One of biodiesel disadvantages is the emission of NOX: studies are being carried out to mitigate this problem.

The performance of engines that use pure biodiesel, however, are 8-15% lower than traditional diesel, due to the different energy contents. In order to solve the above-mentioned problems, a 20% mixture of biesel and biodiesel is used. A mixture of biodiesel, ethanol (up to 15% in volume) and an additive (to help the two substances mix) is called e-diesel.

The mixture is prepared by means of a spray-mixing, a process that does not require any particular equipment nor temperature control. E-diesel largely reduces the emission of particulates as compared to traditional diesel.

Bioproduct

Any compound that can be synthesised from fossil fuels can be similarly produced from biomass. These bioproducts (bioproducts) are therefore produced from renewable energy sources and usually their production needs less energy than their oil-based counterparts.

Researchers demonstrated that the processes to produce biofuel can be combined to obtain antifreeze, plastic materials, glue, artificial sweeteners and toothpaste.

Other reactants to obtain bioproducts are carbon monoxide and hydrogen. They form during biomass heating thanks to the presence of oxygen. This carbon monoxide-hydrogen mixture is known as biosynthesis gas, which gives life to plastic materials and acids that are essential for the production of photo films, textile and synthetic fibres.

When the biomass is heated without oxygen being present, pyrolysis oil is formed, from which phenol can be extracted, i.e. an intermediate used for the production of wood sticks, plastic moulds and insulating foam.

Methanol

Also known as wood alcohol, methanol is usually produced from natural gas, but it can also be synthesised from biomass. The most common process is biomass gasification, that consists of vaporizing biomass at a high temperature, removing hot gas impurities and making it pass through a catalizer that converts it into methanol.

Corrected petrol compounds deriving from biomass act as fuel additives in order to reduce the emission of pollutants.