

Chapter 2

Energy Resources

2.1 Definition of Energy Potential

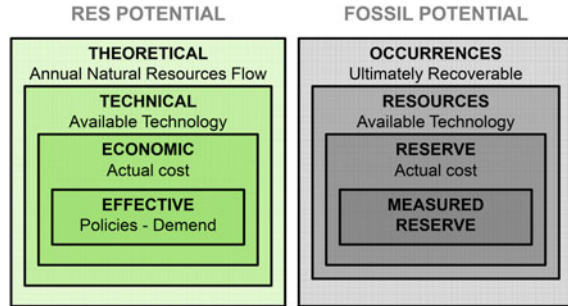
A general assessment of the availability of energy resources¹ is essential for whichever long-term energy policy. As concerns renewable energy sources (RES), the difference vis-à-vis the most widespread fossil sources (RES are regularly-renewed energy flows), whereas fossils can be considered as “fixed” resources) induces to make some preliminary remarks about the definition of RES potential (Fig. 2.1).

The *theoretical potential* of a renewable energy source (like sun, wind, biomass, water, geothermal, etc.) is the annual energy flow without technical–economic references, estimated through a direct analysis. This analysis is made through the maps that take into consideration, respectively, the solar radiation equivalent (annual based), wind speed and distribution, biomass index, water capacity (difference between precipitations and evaporation), hydraulic heads (like differences of geodetic heights), geothermal fields, etc. Some authors add physical and social-economic considerations (slope of the land, eventual road access, presence of electrical grid, gas pipeline and aqueduct proximity to the power plant, etc.) and therefore determine the *theoretical available potential*. For fossil fuels alike, *global occurrences* take into account all the types of resources, either identified or not identified, both economic and not economic (also in this case, the resource available is considered without technical–economic limitations).

The *technical potential* of renewable energy sources is the fraction of the theoretical potential that current technologies allow to exploit. The equivalent for fossil resources is represented by resources (being economic and not economic, identified and not identified, excluding the resources that current technologies do not allow to exploit).

¹ World Energy Council (WEC) in 1998 defined *energy resource* a primary energy source with a demand and conversion and use technology.

Fig. 2.1 Potential of renewable and fossil resources



The *economic potential* is the fraction of the technical potential that is also cost-efficient to exploit. The equivalent for fossils resources is represented by the *reserves* (verifiable, possible and feasible). Finally, the *effective potential* of the RES is the fraction of economic potential exploited, taking into account the demand and the energy policies adopted in each country. As far as fossils are concerned, considering an existing demand and a “favourable” policy, the effective potential is analogous to the *verifiable reserves*, being the resources effectively measured, whose production is possible according to the economic and technological conditions.

Obviously potentials are influenced by several factors (environmental, technical, economic and social), therefore each numerical value changes dynamically according to environmental changes, technological development, market conditions and the relevant political situations.

2.2 The Earth’s Energy Balance

The analysis of energy availability in nature starts from the global energy cycle of the system in which human beings operate: the Earth system. The Earth is not exchanging matter but only energy with the outside, mainly electromagnetic energy from the Sun and releases it in the space (so keeping its average temperature constant). Besides the direct *solarpower* (accounting for around 99.98% of the entire energy available on Earth) the other sources contributing to the energy balance of the Earth for the remaining 0.02% include the energy coming from *gravitational interaction* (practically reduced to the triad Earth, Moon and Sun), as well as the *thermal energy present inside of the Earth*, conveyed to surface through conduction and convection. A further contribution finally comes from *natural radioisotopes* (radioactive elements).

Solar radiation is radiant energy emitted by the Sun from a nuclear fusion reaction that generates electromagnetic energy. The spectrum of solar radiation is close to that of a black body with a temperature of about 5,800 K (according to Wien’s Law, derived from Plank’s Law, the Sun emits radiations with a peak wavelength of 500 nm). About half of the radiation is in the visible shortwave part

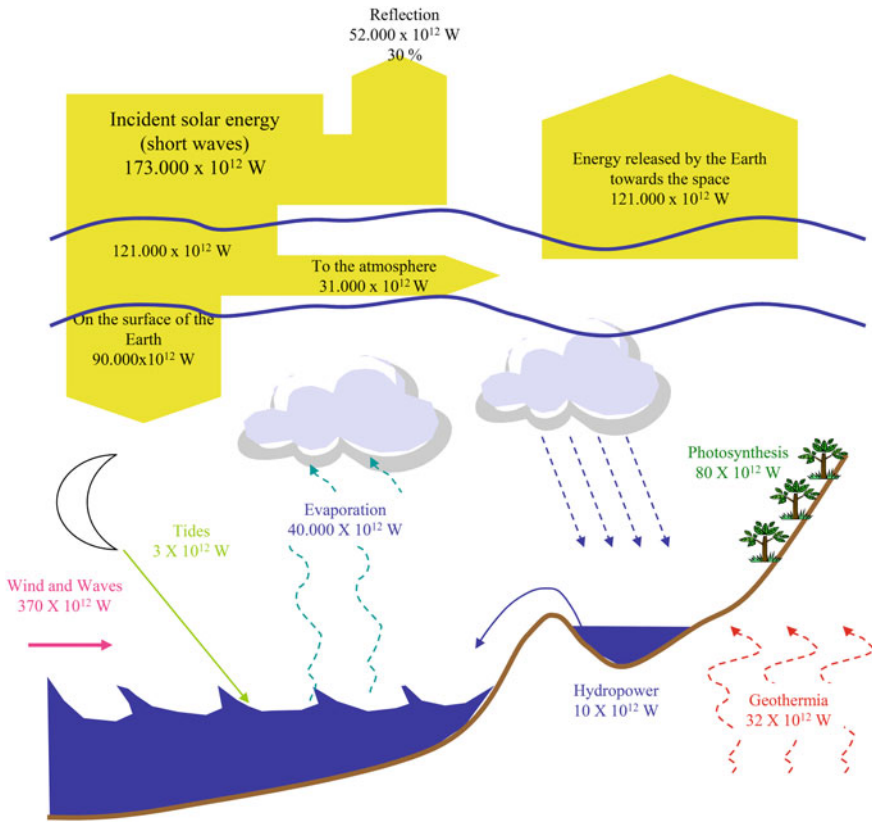


Fig. 2.2 Instant energy balance of the Earth [3]

of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum.

The average energy flow coming from the Sun is called *solar constant* and corresponds to the energy that, outside of the atmosphere (that is to say, without atmospheric absorption phenomena) and at the average distance of the Earth from the Sun, passes through a surface of 1 m^2 , perpendicular to the direction of the flow, in the interval of 1 s. Measurements made through artificial satellites calculated for the solar constant a value of $1,353 \text{ kW/m}^2$, with a $\pm 3\%$ variability due to the ellipticity of the Earth's orbit. Considering the solar constant and the average Earth surface irradiated by the Sun, the estimated amount of the total average power intercepted by the Earth is nearly $173 \times 10^{15} \text{ W}$, to which corresponds an annual incident quantity of $5,404 \times 10^{21} \text{ J/year}$ (that is to $1.3 \times 10^8 \text{ MTOE/year}$).

As shown in Fig. 2.2, nearly 30% of the solar incident radiation is reflected at its arrival and dispersed in the external space under the form of short wavelength radiation (nearly $52,000^{12} \text{ W}$), whereas the remaining part proceeds towards the surface of the earth, through the atmosphere.

The atmosphere, the surface of the Earth, and oceans absorb nearly 47% of the total (nearly $81,000^{12}$ W). Considering that the average insulation at ground level over an entire year (including nights and periods of cloudy weather) is much lower—for example, in North America it ranges between 125 and 375 W/m² (3–9 kWh/m²/day)—and the utilisation of 1% of lands above sea level (for instance through the direct photovoltaic and thermal solar conversion mentioned below), the theoretical potential corresponds to nearly 80×10^{12} W corresponding to an annual energy availability of 5.9×10^4 MTOE/year (values similar to those reported by IEA [1] and Nakicenović et al. [2]).

Twenty three percent (nearly $40,000^{12}$ W) is used in the water cycle that is, to say in the evaporation, precipitation and runoff characterising the hydrologic cycle. The water vapour formed, while raising as a consequence of thermal gradients and of pressure effects, cools beyond the saturation point, and subsequently condenses around ions or dust particles, originating the formation of clouds. When the size of drops reaches at least 1 mm of diameter, atmospheric precipitations (rain, snow and hail) take place in suitable temperature and pressure conditions. The amount of inland precipitations slightly varies according to the different continents by 740–800 mm per year. The two exceptions are South America (1,600 mm per year) and Antarctica (165 mm). Not all the water returns on Earth at the same rate at which it evaporated; a portion of it remains in the upper air, thence allowing its accumulation in the form of potential mechanic energy. Out of the 577,000 km³ of water evaporating from oceans and land surfaces, 119,000 km³ precipitate on the soil. About two-thirds are absorbed in almost equal parts by vegetation and soil; the remaining one-third becomes runoff water. Most of the quantity absorbed by vegetation and soil evaporates again, and this percentage amounts to 72,000 km³. The difference of 47,000 km³ is, in principle, available for energy purposes. The convolution of runoff water allows to take into consideration the theoretical hydropower potential, whose amount (theoretical potential) is estimated as 5×10^{12} W, with an annual energy amounting to 3.6×10^3 MTOE [13]. The largely prevailing energy use of this resource is electricity production in hydroelectric power plants; this is the reason for the word *hydroelectricity*.

A small fraction of the sun energy, amounting to 0.2% (nearly 370×10^{12} W), is destined to winds, ocean circulation, and sea state, and is partly dispersed in the form of frictional heat. Wind is caused by heterogeneous air warming: the air above ground is warmer than air above the sea, and as a consequence of density variation, the warmest air rises and triggers the movement of air masses (AM). A region's mean wind speed and its frequency distribution have to be taken into account to calculate the amount of electricity that could be produced by wind turbines. Wind resources can be exploited in areas where wind power density is at least 400 W/m² at 30 m above the ground. If we consider the exploitable part of wind, then the technical potential is estimated around 15×10^{12} W, to which corresponds an annual energy amounting to nearly 10×10^3 MTOE.

An even lower quantity of the sun energy, nearly $40 \times 10^{12} \text{ W}$ (0.02%), is transformed from the chlorophyll contained in plants that fixes carbon in leaves and stores energy under the form of carbohydrates. Furthermore, this process releases oxygen and, through the decomposition processes, dissipates energy. However, a large quantity of organic matter is stored and accumulated in peat bogs or, in any case, in environments poor in oxygen that do not allow the return to balance conditions. The storage below the crust of the Earth of animal and vegetable remains is at the basis of the complex phenomenon relating to the formation of fossil fuels, which in this way end up storing the solar energy absorbed for millions of years by the Earth. According to estimates, the conversion from *biomasses* might provide $27 \times 10^{12} \text{ W}$ (2×10^4 MTOE per year).

The gravitational systems Earth–Moon and Earth–Sun are at the basis of the phenomenon of tides. The actions of the two systems, however, are combined in an extremely variable way. The movements of the Moon vis-à-vis the Earth take place, in fact, on an orbital level different from the Earth's equatorial plane and, on the other side, because of orbit eccentricity, the periods of the two celestial bodies differ, as well as the mutual distance and the distance to the Sun. Out of the two systems, the Earth–Moon system influences the phenomenon to a higher extend, due to the relative closeness of the Earth from its Satellite (mean distance $384.4 \times 10^6 \text{ m}$), although the mass of the latter is 81.3 times smaller than the Earth's and over 2,500,000 times smaller than the Sun's. As regards the Earth–Sun system, given the higher distance between the two bodies (circa $149 \times 10^9 \text{ m}$), it generates minor tidal forces, although not negligible, in consideration—this time—of the huge mass of the Sun (nearly 333,000 times as much as larger than the Earth's). The other celestial bodies, including those of the solar system, on the contrary, do not have any appreciable influence. Overall, the main gravitational action is the one that the Earth exchanges with the Moon, whereas the Sun only modifies the magnitude of tides. The tidal force peaks when the three celestial bodies are aligned and the lunar attraction adds up to the solar one, whereas it is at minimum levels when the Moon is at its first and last quarter (quadrature), namely when the line connecting the centre of the Earth and the centre of the Moon is perpendicular to the line connecting the centre of the Earth and the centre of the Sun. The level of springtides and of quadrature tides has a deviation of nearly 20%, compared to mean values. The power made instantly available by tides is evaluated as amounting to $3 \times 10^{12} \text{ W}$ (2×10^3 MTOE).

Geothermal power is a so-called energy source “of formation”: in fact this Energy derives from star formation processes that originated the Earth itself. The heat flow coming from the internal part of the Earth was evaluated through geothermal gradient measurements as well as through the thermal conductivity of rocks. Vertically proceeding towards the interior, in the first kilometres a temperature mean increase of 3°C every 100 m is recorded; however, this increase is not constant, since the maximum temperature of the nucleus of the Earth amounts to nearly $4,500^\circ\text{C}$. By means of these measurements, a mean value of the energy flow was determined, amounting to 0.063 W/m^2 ; having considered that the Earth's surface amounts to nearly $510 \times 10^{12} \text{ m}^2$, an overall power of about

32×10^{12} W is obtained, that is $2,4 \times 10^4$ MTOE per year. Thermal sources and volcanoes, however, emit only 1% of total heat, thence the power actually available is reduced to nearly 0.3×10^{12} W. Heat migrates from the hot nucleus of the planet towards the Earth's crust through two main processes: *conduction*, which contributes to a minor extent since rocks are poor conductors of heat, and *convection*, which conversely rapidly spreads thermal energy in fluid materials. Although heat propagation takes place towards the surface of the Earth, and from here towards the space, the temperature inside of the nucleus is rather constant thanks to the contribution of radiations and of the particles released by the radioisotopes present inside of the Earth's crust. Therefore, geothermal energy mainly derives from the decay of radioactive substances inside of the Earth and, having considered the quantities involved, it represents a practically inexhaustible source of energy.

The energy flows and figures making up the energy balance of the Earth are shown in Sankey diagram, where these flows are represented through bands whose width are propotional to the total contribution given by each item. In this framework, another interesting representation is shown, which highlights the water cycle (at the basis of the life on our planet and that, also from the energy view-point, has huge proportions and plays a major role).

It is important to consider the critical aspect of the energy issue: although, at any moment, the power available in nature is—as described afterwards—at least four times as much as higher than the needs of the entire world population, it is technically and/or economically impossible to meet energy needs at any time and for each user, through the only power that is directly made available in nature by the Sun or by the other sources mentioned above.

Meeting energy needs, therefore, is not a problem in terms of quantity but rather of availability of quantity in quality (suitable form), in the space, and at the time needed by users.

2.3 Renewable Sources

2.3.1 Solar Energy (Direct)

If, on the one hand, solar energy has several advantages (such as the absence of polluting agents, the possibility of direct conversion into electric power, a practically unlimited duration as well as a global quantity available far higher than human kind's energy needs), on the other hand several problems must be overcome for its widespread use, including technical and economic ones, linked to the low energy density, and to its discontinuity (night/day alternation, seasons cycle, variation in weather conditions). It is clear, then, how big is the gap between potential availability and practical possibilities of use.

2.3.1.1 Overview

As already mentioned in Sect. 2.2, outside of the Earth's atmosphere the incident power on an area perpendicular to the direction of Sun rays slightly exceeds $1,300 \text{ W/m}^2$ and this value is named *solar constant*. In its passage through the atmosphere, however, the spectrum of solar radiation changes both quantitatively and qualitatively. More in detail, the interaction of solar radiation with the earth's atmosphere and surface is mainly determined by 3 groups of factors:

1. The Earth's geometry, revolution and rotation (declination, latitude, solar angle);
2. Terrain (elevation, surface inclination and orientation, shadows).
3. Atmospheric attenuation (scattering, absorption) by:
 - a Gases (air molecules, ozone, CO_2 and O_2).
 - b Solid and liquid particles (aerosols, including non-condensed water).
 - c Clouds (condensed water).

The first group of factors determines the extraterrestrial radiation available according to the solar position above the horizon, and it can be precisely calculated through astronomic formulas.

The radiation input to the Earth's surface is then modified by the topography of its terrain—namely slope, inclination and aspect—as well as by the shadowing effects of neighbouring terrains. This group of factors can also be modelled at a high degree of accuracy. The elevation above the sea level determines the attenuation of radiation by the thickness of the atmosphere.

The intensity of the extraterrestrial solar radiation passing through the earth's atmosphere is attenuated by various atmospheric constituents, namely gases, liquid and solid particles and clouds. The path length through the atmosphere is also critical. Because of its dynamic nature and complex interactions, the atmospheric attenuation can be modelled only at a certain level of accuracy.

The quality of radiation, that is to say the distribution of wavelengths in the solar spectrum, undergoes a variation due to the scattering phenomenon, based on which the photons of different wavelengths are spread according to different angles. The radiation that reaches the ground has then a different composition from the radiation originally released by the sun.

To quantify the spectrum of ground radiation, reference is often made to the concept of AM: it is defined as the ratio between the length of the real path of Sun rays and the length of their shortest possible path, that is to say with the Sun at the zenith. By convention, it is agreed that outside of the atmosphere the solar spectrum has an AM equal to 0. At the sea level, on a clear summer day, the radiation coming from the Sun at the zenith corresponds to AM1, whereas other positions correspond to an AM of $1/\sin h$, where h is the zenith angle (Fig. 2.3). As a reference magnitude for the measurement of cells and of photovoltaic modules, an AM of 1.5 is used.

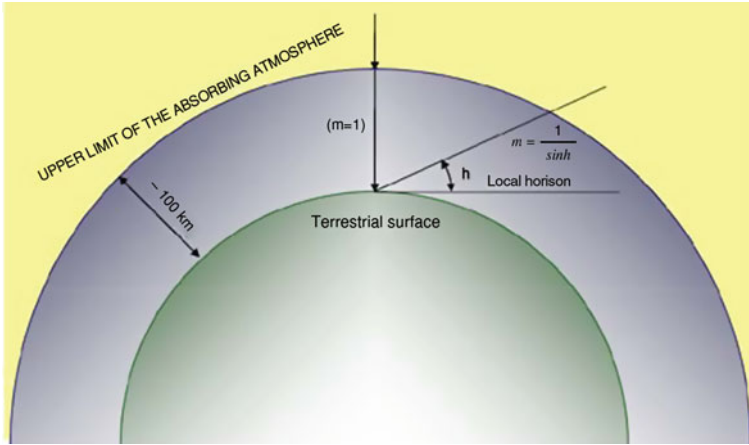
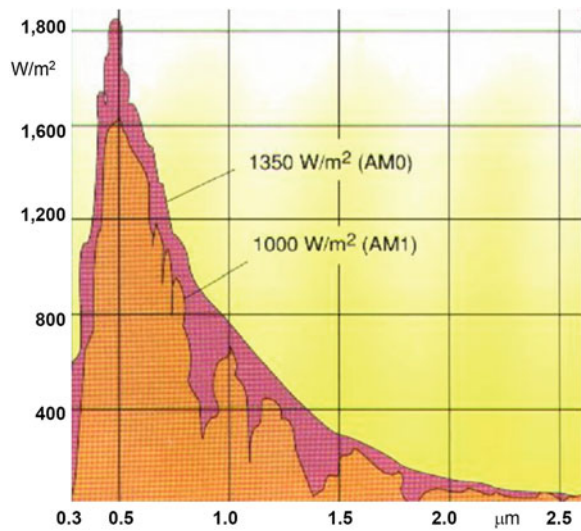


Fig. 2.3 Air mass (AM) and schematization of the solar radiation incidence angle

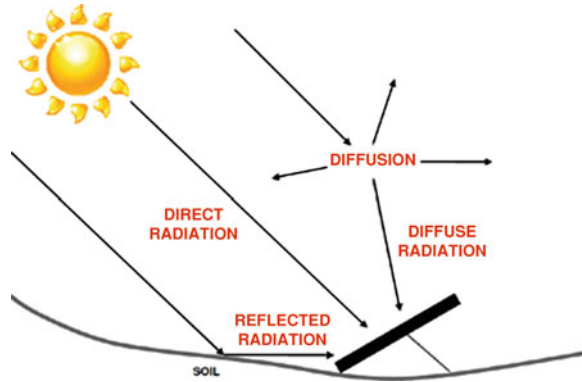
Fig. 2.4 Comparison between the extra-atmospheric solar spectrum (AM0) and a ground solar spectrum at ground level (AM1)



An interesting comparison concerns (Fig. 2.4) the extra-atmospheric solar spectrum (AM0) and an atmospheric solar spectrum (AM1), where the already mentioned qualitative and quantitative differences between the two radiations are highlighted.

The radiation impacting on a given surface, called *global solar radiation*, is the sum of three components (Fig. 2.5). The component that is neither absorbed nor spread by atmospheric particles, and that directly reaches the surface in question with a single and well-defined angle, is called *direct radiation*. The component

Fig. 2.5 The components of solar radiation



that, through the atmosphere, is deflected in random directions (scattering), mainly due to the particles of water vapour in the air, but that in any case succeeds in impacting the surface, is named *diffuse* radiation. The grey areas, that is to say the areas of surfaces not reached by direct radiation due to the presence of hindrances, are not completely darkened, also thanks to the contribution of diffuse radiation. The radiation that reaches the surface after being reflected by the ground or by other surfaces is called *reflected* radiation. As concerns the tendency to reflect incident energy, the major contribution is given by light surfaces (for instance, areas covered with snow in winter) whereas dark surfaces (as ploughed fields or grasslands) are characterised by a high absorption coefficient.

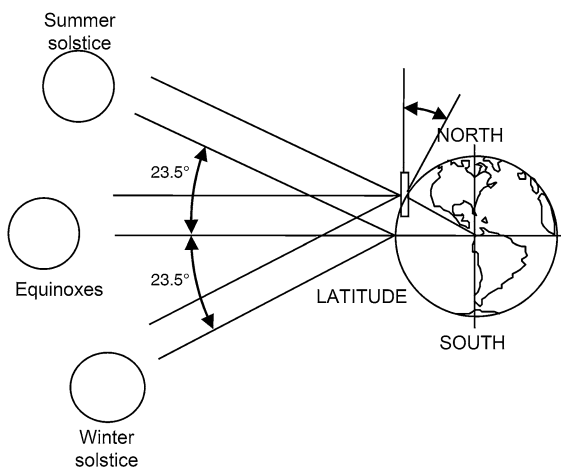
The relative importance of these three components varies depending on:

- *Weather conditions* In a cloudy day, the diffuse component prevails over the direct one.
- *Inclination of the collector surface* During summer months, a surface with a minor inclination on the horizontal plane shows a higher contribution of direct radiation, and the opposite happens in winter months.
- *Period of the year* In a collector surface placed vertically, the contribution of direct radiation will be lower in summer months, and the opposite applies in surfaces with a minor inclination.
- The global value of the radiation reaching the ground is subject to:
 - Regular variations (daily and annual) due to the apparent motion of the Sun in the sky.
 - Irregular variations due to weather conditions (cloudiness, humidity, etc.).

The position of a surface that allows to maximise the quantity of solar radiation collected is the one in which this surface is oriented southward,² with a tilt angle

² This condition is true for the regions of the Northern Hemisphere placed north of the Tropic of Cancer (lat. 23°27'N); in the regions of the Southern Hemisphere placed south of the Tropic of Capricorn (lat. 23°27'S) the suitable orientation is northward; finally, in case of the regions of the tropical zone, it depends on the period of the year.

Fig. 2.6 Radiation variations depending on the annual oscillation of the earth's axis



equalling the latitude of the site. Orientation optimises reception during the entire day, whereas inclination minimises the radiation variations due to the annual oscillation of the earth's axis that determines a variation in the direction of Sun rays compared to the vertical axis (Fig. 2.6).

2.3.1.2 Resource Evaluation

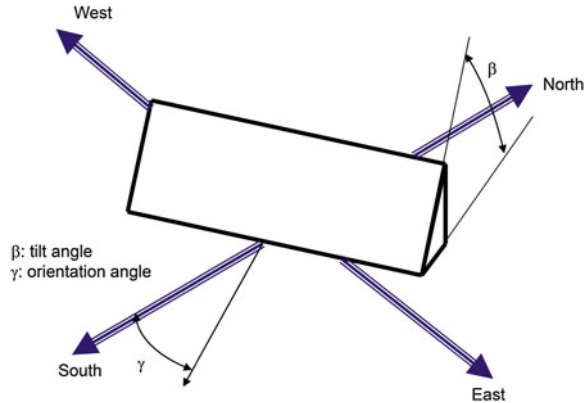
Let us turn now to the calculation of global solar incident radiation on a surface placed in any position. Clearly, this is the most interesting calculation for the evaluation of electric power production potential by a photovoltaic system installed in a given site.

The main sources to estimate the incident solar radiation in a given period on a surface are the Solar Radiation Atlas. They collect data mostly provided by national meteorological institutes or, in exceptional cases, by universities. This set of data is collected in maps and tables, and usually derives from 10-yearly measurements. In the case of Europe, the European Solar Radiation Atlas is divided into two volumes: the first one relates to horizontal surfaces; the second volume concerns tilt surfaces. In the first volume of the Atlas tables show the values of mean daily radiation for each place considered, expressed in Wh/m^2 (or kWh/m^2), that is to say in *energy density*.

Each place is characterised by its coordinates (latitude and longitude), and by its altitude above the sea level. The most important value is the one appearing in the first row of each table, indicated with letter G. It expresses the mean daily radiation and is shown for each month and then as annual mean value.

The values of incident global radiation on a horizontal surface; however, have a limited interest for the design and development of photovoltaic systems, since, in order to optimise their electric output, these systems are always arranged with a certain

Fig. 2.7 Angles characterising the position of a surface



inclination on the horizontal plane. Therefore, the determination of the incident solar energy on a tilt surface with a given angle becomes of paramount importance.

This problem can be solved through two different approaches: the consultation of the second volume of the European Solar Radiation Atlas, or the mathematical calculations of the radiation on a tilt surface starting from the corresponding data for a horizontal surface.

The first approach resorts to the second volume of the Atlas, which refers to tilt surfaces. For each place, tables show the mean daily radiation (both global and diffuse) per each month and on an annual basis, corresponding to different positions of the collector surface. This position is characterised by two angles (Fig. 2.7):

- The tilt angle (shown in the figure with letter β) that measures the tilt of the surface considered, as compared to a horizontal plane.
- The orientation angle (or azimuth, shown in the figure with letter γ), which indicates the orientation of the surface vis-à-vis the cardinal points (the orientation southward corresponds to a null azimuth); more precisely, it is the angle that the projection on the horizontal plane of the normal surface forms with the southward direction in the northern hemisphere (or northward in the southern hemisphere).

In order to know the values of solar radiation according to the reference geographical site, suitable maps, called *iso-radiation* maps, are used. Radiation values mainly depend on orographic characteristics and, to a lower extent, on latitude variations.

It is necessary to specify that, in most of data available, no distinction can be made between the component of direct radiation of diffuse radiation.

Maps show the distribution of daily mean radiation for the different months and on an annual basis (Fig. 2.8). The black lines in the maps are the isoradiative

Fig. 2.8 Solar geographical information system

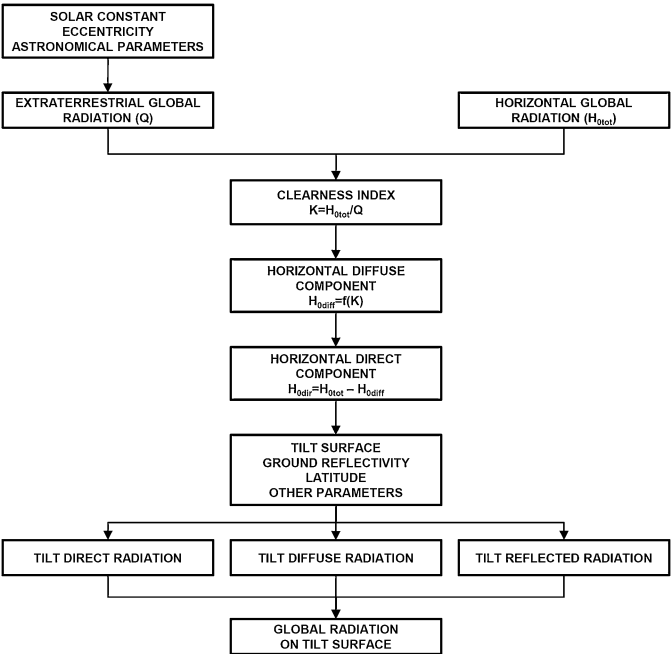
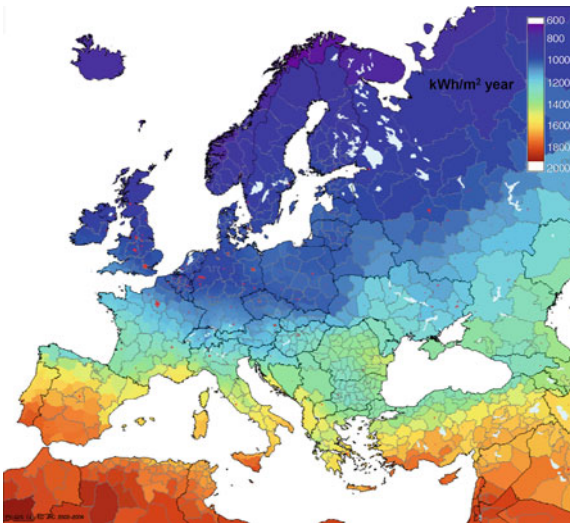


Fig. 2.9 Procedure for the calculation of the global solar radiation on a tilt surface

curves that is, to say lines indicating the constant value of the mean daily radiation, measured in kWh/m².

Note that the values shown in the second volume of the European Atlas were calculated by hypothesizing a fixed value for ground reflectivity, amounting to 0.2

(meaning that the ground reflects 20% of incident radiation; a value corresponding to a grassland). If the site in question shows a different reflectivity, corrective formulas shall be used to determine the exact value of the reflected component. However usually the reflected component provides global radiation with a rather limited contribution, amounting to a few percentage points.

The second approach for the determination of solar radiation on a tilt surface is the calculation starting from the data on a horizontal surface, which in turn can be derived from the Solar Radiation Atlas.

Without lingering on the detail of the calculation procedure, here it follows a short description of the fundamental steps at the basis of this approach (Fig. 2.9).

The first step consists in determining the extra-atmospheric radiation starting from the evaluation of a few astronomic parameters as the eccentricity of the earth's orbit. The comparison between the global values of extraterrestrial radiation and the incident radiation on a horizontal surface shows the so-called "*clearness index*".

The diffuse component of radiation (always on a horizontal surface) is then calculated as a complex function of this newly-determined index. The direct component is found as a difference between the global and the diffuse radiation. At this point of the procedure, the three components of solar radiation on a horizontal surface are taken into consideration. It is then possible to calculate, through rather complex formulas, the values of these three components for a given surface arranged in space. Different input parameters are necessary in this calculation phase, and in particular surface tilt, ground reflectivity (for the determination of the levels of the reflected component) and the latitude of the installation site.

2.3.2 Hydropower

The rain and the snow give origin to the water flowing on our planet's lands. The quantity of precipitations, the configuration of the territory and its type of rock or ground, are the factors that determine the characteristics of a watercourse. It is therefore important to know "how much water falls" on a territory to imagine and plan the use of this resource that is so important for all the human kind. The measurement of precipitations is indicated in millimeters of water, and is carried out in the "Precipitation Stations" suitably installed throughout the territory.

As mentioned in Sect. 2.2, hydropower directly depends on the portion of solar radiation that originates the *water cycle on Earth*. This resource is, to all intents and purposes, a *renewable source*; but, due to its intensive use in electricity production, it is traditionally included among *conventional* energy sources.

In the last few years, a renewed interest was expressed vis-à-vis the use of water basins that can fuel small plants with a maximum power of 3,000 kW. *Mini-hydraulic energy* (or minihydro is the name of the branch dealing with these plants) can, in fact, remarkably contribute to the electrification of developing countries, where small-sized isolated users are present, although almost lacking in a distribution grid linking them to large plants. Finally, particular importance is

ascribed to water basins or watercourses that can fuel very small plants of tens of kW, *micro-hydraulic plants*.

2.3.2.1 Overview

Drainage Basins

River courses always develop at valley bottoms, having considered that water flows due to the effect of gravitational forces; the valley where the river flows, and the mountains surrounding it, up to the watershed peak, is called *catchment area*.

Through the analysis of the basin ground and the measurement of precipitations in that given area, it is possible to define the behaviour of the river and the quantity of water that can be used.

A watercourse can be named in different ways: river, torrent, brook etc.; each of these names indicates its different characteristics dealing with the continuity of the flow rate, its volume and the size of the watercourse itself.

2.3.2.2 Resource Evaluation

The study of water resources is fundamental, and involves the science of hydrology, the study of rainfall and stream flows, the measurement of drainage basins, catchments, evapotranspiration and surface geology. While flowing from point A to point B of a watercourse, water loses potential energy according to (2.1). This available power can be converted, by limiting friction, into useful kinetic energy.

$$P = Q \cdot \rho \cdot g \cdot H \quad (2.1)$$

In (2.1), P is the power [W], Q the flow in [m³/s], ρ the water density (1,000 kg/m³), g the acceleration of gravity (9.81 m/s²) and H the gross head [m] (the vertical useful difference in level). Therefore, to estimate the water potential, it is necessary to know the variation of the discharge throughout the year as well as level of the gross available head. A United Nations Organisation was established—the World Meteorological Organisation—providing hydrologic information service besides National Hydrological Services, River Basin Authorities and other institutions, but it is unusual to make regular gauging in the stretch of river where the development of a small hydro scheme is proposed. Thus, normally, through the models of local data in terms of *precipitation* (monthly rainfall), *evaporation* discharge (linked to temperature values, etc.), *stage* (water level), *sediment and water quality* and *groundwater of the areas*, it is possible to calculate the variation of the discharge throughout the year and the available head. Generally, an area with mountains and high precipitation has several good hydropower sites (Fig. 2.10).

To estimate the hydroelectric potential of a site, the annual variation of the flow rate during the year must be known, as well as the gross head available. In the best

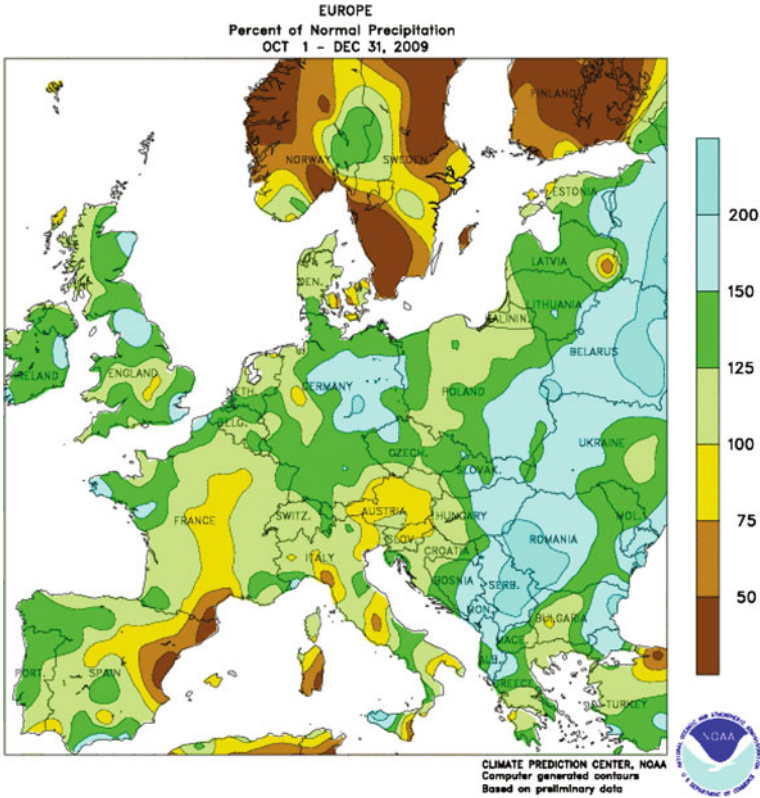


Fig. 2.10 World hydrological cycle observing system

of cases, the drainage services have installed a measurement station, and the historical series of effluent flow rates will be collected. In case of unknown hydrological data, the flow rate for at least one year will have to be measured.

Equation 2.1 clearly shows the power (and thence the energy) obtainable as determined by the *head* (H) and by the *flow rate* (Q) of the watercourse considered.

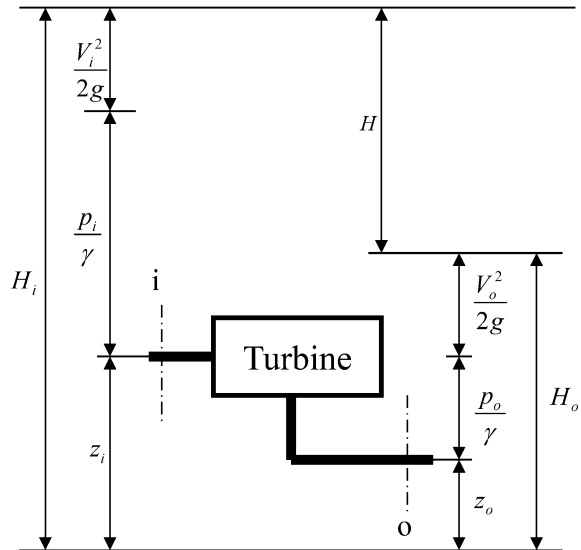
The head is the difference in level between the point of water inlet and the point of water outlet [m].

Hydroelectric power plants are divided according to the value of this size into:

- High head over 100 m
- Medium head 30–100 m
- Low head 2–30 m

The flow rate taken from a hydroelectric plant is the water volume taken in a time unit [m^3/s]. According to the flow rate, reference is made to

- Small flow rate up to $10 \text{ m}^3/\text{s}$
- Medium flow rate from 10 to $100 \text{ m}^3/\text{s}$

Fig. 2.11 The net head

- Large flow rate from 100 to 1.000 m³/s
- Very large flow rate over 1000 m³/s

Various methods can be used for flow rate measurement:

- *Area–velocity method*, used for medium and large rivers, it consists in the measurement of the cross-section of the river and the medium velocity of water. The section is detected through topographic methods, whereas the mean speed can be measured through different tools: float, swivel and electromagnetic meters.
- *Direct measurement of flow rates through dilution of a solute in the current*. Suitable for small watercourses characterised by turbulent flow; the simplest method consists in the dilution of common salt in water and in the subsequent measurement downstream of the electrical conductivity of the solution formed;
- *Measurement through overflow*, if the river is small enough, it is possible to make a provisional weir and allow the water to flow through a known section (the overflow); through measurements on the geometry of the system, it is possible to trace back the flow rate;
- *Slope–area measurement*, this method is suitable for high flow rate values and is based on the principles of hydraulics.

2.3.2.3 Net Head

The net head of a hydraulic turbine is the difference of hydraulic loads, namely of fluid mechanic energy, between two conventional sections taken before and after the machine.

In relation to Fig. 2.11, the net head is obtained as follows:

$$\frac{V_i^2}{2g} + \frac{p_i}{\gamma} + z_i = \frac{V_o^2}{2g} + \frac{p_o}{\gamma} + z_o$$

2.3.3 Wind

The power owned by the wind, so called *wind energy*, has been used by men since ancient times for purposes ranging from sailing (Egyptian images of 2,500 BC.) to the winnowing of cereals, to the drying of farming and fishery products.

Windmills in Europe first appeared in the middle ages, at the time of crusades. Completely different from the conceptual viewpoint, with horizontal-axis wheels, these windmills were larger in size, technologically more complex, with a higher yield. They were used for the grinding of cereals, olive pressing, water pumping, setting in motion and operation of sawmills, paper mills, dye-works and tobacco industries.

In the last century, multi-blade rotor ram-air turbines became widespread, subsequently used in large numbers in the farms of newly colonized territories.

A further step forward in the transition from windmills to modern aero-generators was made in Denmark by Paul La Cour, between 1891 and 1907. His rotor had four rectangular warped blades, typical of a European wind mill.

During World War II, some studies were launched in the USA, in the Netherlands and in Denmark that—boosted by the problems of a war economy—led to the design and development of machines (at that point *aerogenerators*) with two-bladed and three-bladed rotors.

In 1924, the Finnish engineer Savonius tested a new and innovative type of *vertical-axis aerogenerator*.

Another type of rotor, Darrieus, derives from an original plan dating back to the beginning of the '30 s by Darrieus. At the moment, it represents the only vertical-axis machine able to really counter the supremacy of the HAWT (Horizontal Axe Wind Turbine).

The possibility of exploiting the wind source with directly competitive costs, or at least costs comparable to conventional sources, is heavily limited by its *low energy density* (in the windiest areas, it is possible to reach the maximum³ value of 400–600 W/m²), as well as by its marked *changeableness and uncertainty*, also while considering seasonal and annual mean values. Furthermore, there is also the problem of *windblasts* that is, to say winds whose high and suddenly variable intensity generate—in wind power plants—mechanical resistance problems and may also cause breakings.

³ These are annual mean values of power per surface unit affected by the blades of a wind machine.

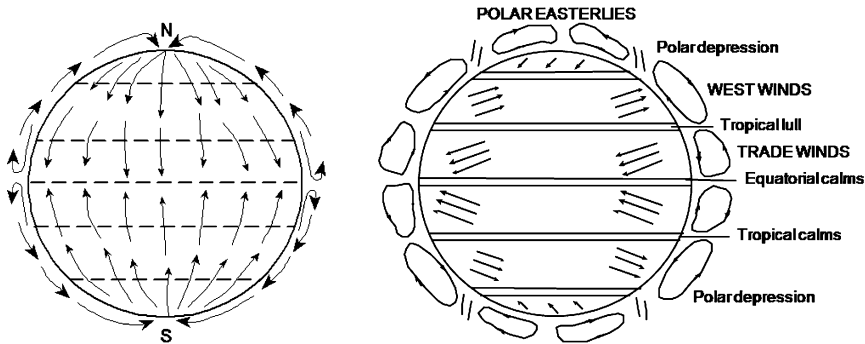


Fig. 2.12 Wind circulation linked to phenomena operating at the Earth level (Source: ENEL SpA)

From a merely operational viewpoint, a fundamental step to usefully exploit the wind source is the choice of the suitable place where installing conversion plants, that is to say the determination of a suitable choice of the site.

2.3.3.1 Overview

Wind energy means the kinetic energy owned by AM moving in the Earth's atmosphere. In general, their movement is linked to the action of atmospheric pressure, or better, pressure gradient, and therefore of temperature, in the sense that air tends to move from high-pressure areas to low-pressure adjacent areas, with a speed related to such gradient.

The wind and its main characteristics, namely *intensity* and *direction*, depend upon several factors acting at a local and global scale.

The most important factor is *solar radiation and its different intensity*, higher in the equatorial zone and lower in the areas close to the poles. The Earth's surface releases to the atmosphere part of the heat received from the Sun; the equatorial air, warmer thus with a lower density, tends in any case to rise, generating a depression that attracts other AM from the poles, and triggering—at the planet level—a *circulation of cold air from polar zones to the equator*.

Among the other factors influencing the circulation of winds, from a global viewpoint, there are the *inclination of the Earth axis* and the movement of *revolution around the Sun*, which seasonally move the most insulated areas inside of the tropical zone. On the contrary, the movement of *rotation of the Earth* determines a daily alternation of solar radiation, and induces the *Coriolis complementary acceleration* on the moving AM, producing the typical *spiral* movement of wind currents; the *lack of uniformity and homogeneity of the earth's surface* is finally responsible for the different absorption capacity and for the exchange of solar heat between the Earth and the atmosphere above it.

Fig. 2.13 Wind speed variation according to the distance from the ground

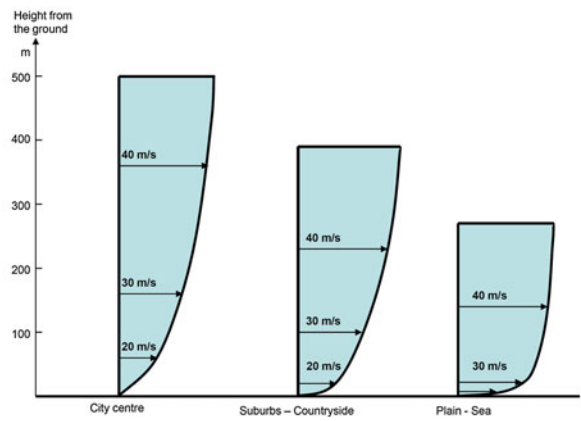


Fig. 2.14 Anemometers

Figure 2.12 shows a global representation of wind circulation due to high and low pressure flows,⁴ which develop at a regional level as a consequence of the phenomena mentioned above.

⁴ As regards Fig. 2.12, there are in particular one zone of low pressure at the equator; two tropical areas of high pressure; two areas of low pressure in sub-polar zones; two high pressure zones on the polar caps.

Table 2.1 Beaufort scale

Force	Equivalent speed 10 m above ground		Description	Specifications for use on land	Specifications for use at sea
	miles/hour	knots			
0	0-1	0-1	Calm	Calm; smoke rises vertically	Sea like a mirror
1	1-3	1-3	Light air	Direction of wind shown by smoke drift, but not by wind vanes.	Ripples with the appearance of scales are formed, but without foam crests.
2	4-7	4-6	Light breeze	Wind felt on face; leaves rustle; ordinary vanes moved by wind.	Small wavelets, still short, but more pronounced. Crests have a glassy appearance and do not break.
3	8-12	7-10	Gentle breeze	Leaves and small twigs in constant motion; wind extends light flag.	Large wavelets. Crests begin to break. Foam of glassy appearance. Perhaps scattered white horses.
4	13-18	11-16	Moderate breeze	Raises dust and loose paper; small branches are moved.	Small waves, becoming larger; fairly frequent white horses.
5	19-24	17-21	Fresh breeze	Small trees in leaf begin to sway; crested wavelets form on inland waters.	Moderate waves, taking a more pronounced long form; many white horses are formed. Chance of some spray.
6	25-31	22-27	Strong breeze	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	Large waves begin to form; the white foam crests are more extensive everywhere. Probably some spray.
7	32-38	28-33	Near gale	Whole trees in motion; inconvenience felt when walking against the wind.	Sea heaps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
8	39-46	34-40	Gale	Breaks twigs off trees; generally impedes progress.	Moderately high waves of greater length; edges of crests begin to break into spindrift. The foam is blown in well-marked streaks along the direction of the wind.

(continued)

Table 2.1 (continued)

Force	Equivalent speed 10 m above ground		Description	Specifications for use on land	Specifications for use at sea
	miles/hour	knots			
9	47-54	41-47	Severe gale	Slight structural damage occurs (chimney-pots and slates removed).	High waves. Dense streaks of foam along the direction of the wind. Crests of waves begin to topple, tumble and roll over. Spray may affect visibility.
10	55-63	48-55	Storm	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	Very high waves with long over-hanging crests. The resulting foam, in great patches, is blown in dense white streaks along the direction of the wind. On the whole the surface of the sea takes on a white appearance. The 'tumbling' of the sea becomes heavy and shock-like. Visibility affected.
11	64-72	56-63	Violent storm	Very rarely experienced; accompanied by wide-spread damage.	Exceptionally high waves (small and medium-size ships might be for a time lost to view behind the waves). The sea is completely covered with long white patches of foam lying along the direction of the wind. Everywhere the edges of the wave crests are blown into froth. Visibility affected.
12	73-83	64-71	Hurricane	- -	The air is filled with foam and spray. Sea completely white with driving spray; visibility very seriously affected.

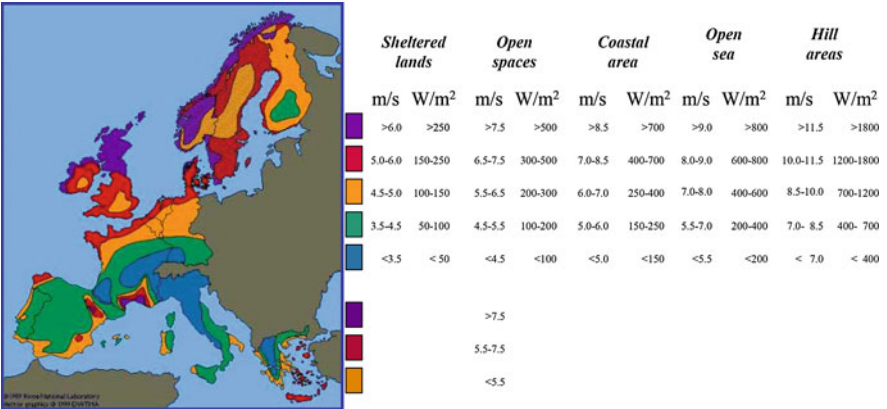


Fig. 2.15 Example of a wind map

2.3.3.2 Resource Evaluation

The last factor recalled that is, to say the varied and uneven type of the Earth’s crust (oceans, lands above sea level with mountain chains, valleys, plains and depressions, glaciers, etc.) also acts on a local scale, together with other elements as *frictional force* and *orography*. The frictional force, due to the *roughness* of the earth’s surface, determines a dissipation of the energy of wind currents, as well as the development of a border layer of the atmosphere (1–1.5 km of thickness), inside of which wind speed increases with height and its trend can be represented through a logarithmic function (Fig. 2.13).

The most immediate way to quantify the wind consists in measuring its speed. To this end, devices called *anemometers* were developed, the most common types of which are shown in Fig. 2.14.

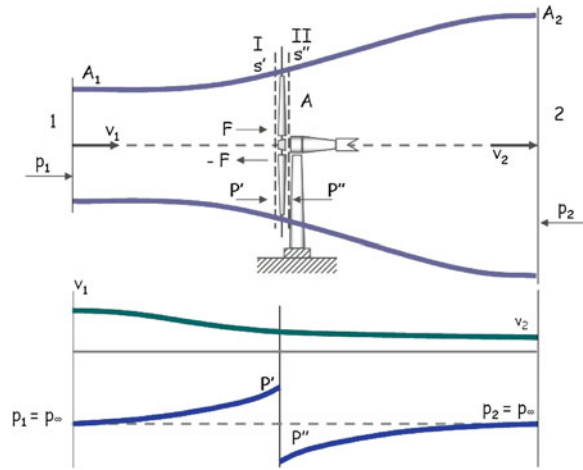
Approximate expeditious measurements of wind speed can be made through the Beaufort scale (Table 2.1).

Wind up to 5 m/s (breeze) is a low wind (scarcely perceivable: thus class 1 areas are unsuitable for wind energy development); from 5 to 15 m/s (around 54 km/h) is a “normal” wind (but only areas designated as class 4 or greater are suitable with the actual wind turbine technology; class 2 and 3 areas may be suitable for future technologies, and over is the storm range (35 m/s, i.e., 126 km/h is normal speed of a hurricane; these values are very rare).

On the basis of the measurements made through anemometers, the *isoveLOCITY curves* are defined. The measurements made in a place are extended to the neighbouring areas under suitable hypotheses and through the use of suitable models (Fig. 2.15).

To evaluate the energy provided by the wind, some quantitative analyses have to be made, starting from the physical and geographical values involved. In this connection, the two following theorems are referred to:

Fig. 2.16 Stream tube, velocity and pressures in an aerogenerator



- *Froude's theorem*: the speed of fluid vein at the level of the propeller disk equals the arithmetic mean of the speed that the fluid vein has upstream and downstream the blade itself.
- *Betz theory*: the maximum possible energy derived from the wind for a windmill is 0.59 of the power available.

Froude's theorem can be demonstrated by assuming the following hypotheses:

- Fluid density, due to the limited velocity variations, is considered as constant.
- The flow rate inside of the stream tube is constant.
- Energy exchanges are only axial that is, to say the variations in momentum are only axial.
- The propeller has infinite blades.
- There are no rotational motions.

The analysis of pressure distribution shows that:

- The fluid vein stresses the windmill with a strength amounting to F
- The windmill stresses the fluid vein with a strength amounting to $-F$
- The fluid vein holds back both upstream and downstream.

All this determines that:

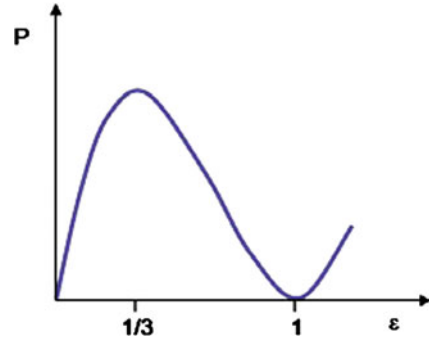
- The stream tube takes the shape of a bottleneck (for continuity).
- Velocity variation is continuous along the stream tube.

As regards Fig. 2.16 the pulse theory is applied to the windmill. According to the law of continuity, it follows that:

$$A_1 \cdot V_1 = A_2 \cdot V_2 = A \cdot V = \cos t \quad (2.2)$$

By applying the pulse theory between sections 1 and 2 and sections I and II

Fig. 2.17 Power available according to the loss of velocity ε



$$\rho \cdot A \cdot V \cdot (V_2 - V_1) = -F \quad (2.3)$$

$$\rho \cdot A \cdot V \cdot (V - V) = 0 = A \cdot p' - A \cdot p'' - F \quad (2.4)$$

From (2.4) it can be easily derived that:

$$F = A \cdot (p' - p'') \quad (2.5)$$

By applying the Bernoulli's theorem between a section upstream the blade (undisturbed flow) and section s' , and between section s'' and a section downstream the blade (undisturbed flow), it follows:

$$p_1 + \frac{1}{2} \rho V_1^2 = p' + \frac{1}{2} \rho V^2 \quad (2.6)$$

$$p_2 + \frac{1}{2} \rho V_2^2 = p'' + \frac{1}{2} \rho V^2 \quad (2.7)$$

Subtracting (2.7) from (2.6), therefore:

$$\frac{1}{2} \rho \cdot (V_1^2 - V_2^2) = p' - p'' \quad (2.8)$$

By replacing (2.8) in (2.5) it is obtained:

$$F = \rho \cdot A \cdot V \cdot (V_1 - V_2) = \frac{1}{2} \rho \cdot A \cdot (V_1^2 - V_2^2) \quad (2.9)$$

From which it is possible to easily derive the V expression, amounting to the mean of the velocity that the fluid vein owns upstream and downstream the blade:

$$V = \frac{1}{2} \cdot (V_1 + V_2) \quad (2.10)$$

To demonstrate the Betz theory, please consider, while recalling (2.9), the expression of the power available to the blade:

$$P = F \cdot V = \frac{1}{2} \rho \cdot A \cdot V \cdot (V_1^2 - V_2^2) \quad (2.11)$$

The velocity of the fluid vein decreases along the stream tube. Indicating the percentage of loss (as compared to the value of the velocity of the undisturbed flow upstream the blade V_1) with ε , it is possible to express V and V_2 according to V_1 :

$$V = V_1 - V_1 \varepsilon = V_1 \cdot (1 - \varepsilon) \quad (2.12)$$

$$V_2 = V - V_1 \varepsilon = V_1 \cdot (1 - 2\varepsilon) \quad (2.13)$$

By replacing (2.12) and (2.13) in (2.11) it follows:

$$P = 2 \cdot \rho \cdot A \cdot V_1^3 \cdot \varepsilon \cdot (1 - \varepsilon)^2 \quad (2.14)$$

The trend of power available according to the loss of velocity ε is shown in Fig. 2.17. Deriving (2.14) compared to ε and equating to zero, the values of ε are obtained to which correspond the minimum and the maximum of the power available.

$$\frac{\partial P}{\partial \varepsilon} = 2 \cdot \rho \cdot A \cdot V_1^3 \cdot (1 - \varepsilon) \cdot (1 - 3\varepsilon) \quad (2.15)$$

This derivative is null for

$$1 - \varepsilon = 0 \Rightarrow \varepsilon = 1 \quad (2.16)$$

$$1 - 3\varepsilon = 0 \Rightarrow \varepsilon = \frac{1}{3} \quad (2.17)$$

As shown in the chart of Fig. 2.17, the value $\varepsilon = 1$, corresponds to a minimum value of the power available ($P = 0$), whereas for $\varepsilon = 1/3$, there is a maximum of the power that can be supplied. It is evident that (2.14) is null for $\varepsilon = 1$ and for $\varepsilon = 0$. By recalling (2.12) and (2.13), for $\varepsilon = 0$ it follows:

$$V = V_1 = V_2 \quad (2.18)$$

The velocity and therefore the kinetic energy of the air remains constant: in this case the power is null since there is no energy exchange between the AM and the blade. For $\varepsilon = 1$, on the contrary:

$$V_2 = 0 \quad (2.19)$$

This means that in this case the power is null since the flow rate is null.

Assuming $\varepsilon = 1/3$ in (2.14) the maximum value of the power available is obtained. This value represents the limit of Betz.

$$P = \frac{1}{2} \cdot \rho \cdot A \cdot V_1^3 \cdot \frac{16}{27} = 0,59 \cdot \left(\frac{1}{2} \cdot \rho \cdot A \cdot V_1^3 \right) \quad (2.20)$$

This shows that the maximum power that a windmill can take from the wind accounts for 59% of wind power.

Equation 2.20 shows that power increases by a factor of three as wind speed increases, and it is proportional to air density and to the swept area (for a HAWT the area through which the rotor blades pass by the rotors). Because of the low air density (1.25 kg/m^3), *wind power density is much lower than water power* (1.000 kg/m^3). If the *diameter* of the rotor blades is *doubled*, the power increases by a factor of *four*. If the wind *speed* then *doubles*, power increases by a factor of *eight*.

The wind source is an intermittent energy source, with characteristics of space–time uncertainty, and therefore characterised by its own availability in time that can be very much variable although within the statistical limits of the phenomenological. Therefore, the following definitions apply:

- *Maximum resource available*: fifty nine percent of the energy actually contained in the incident flow.
- *Resource actually available*: the resource that, following the meteorological phenomena related to local and global climate, is present on the site.
- *Accessible resource*: the resource obtained by applying to the maximum resource the maximum efficiency of present machines.
- *Actual accessible resource*: the one obtained by applying to the resource actually available the maximum efficiency of present machines.

2.3.4 Biomass

The word *biomass* indicates each and every organic matter, either vegetal or animal, in a non-fossil form. Biomass represents the most ancient energy form ever known by human beings. By storing solar energy in chemical bonds, it also represents the most sophisticated form of energy storage in nature. In fact, through photosynthesis, plants containing chlorophyll convert water and CO_2 into organic matter during their growth, that is to say they use solar energy to create long chains mainly made up of carbon, oxygen and hydrogen. However, only one part of the solar spectrum (45%) intervenes in photosynthesis and a further 20% is lost due to reflection or poor absorption phenomena. Therefore, the yield of this process is low (between 0.1% (world average) and 1% (crops)); however, due to the large spreading of biomasses, energy values are considerable. In this way, in fact, nearly 2×10^{11} tons of carbon are “fixed” overall every year, and 120 Gt of biomass are produced with an energy content of 70×10^9 TOE distributed as follows:

- 50% in water
- 35% in forests
- 10% in savannahs and grasslands
- 5% in farmlands.

In consideration on its distribution in the planet, biomass is the most common form of renewable energy, and the main reservoir of solar energy. Although the real ratio of compounds varies from species to species, on average biomass is made up 75% by carbohydrates or sugars and 25% by lignin.

Since ancient times, the residues of organic matters derived from the photosynthesis activity—either direct (plants) or indirect (animals)—have been used for heat generation and for the production of derived solid, liquid and gaseous fuels. They represent the most sophisticated form of storage of solar energy and, therefore, renewable primary energy sources.

Also wood, considered as an energy source, falls within the most general category of biomass. As it happens with the other *non-commercial* sources, even in case of wood it is difficult to determine its market value and include it in official energy statistics. One of the main reasons shall be sought in its energy characteristics and, most of all, in its limited calorific value,⁵ which among other things varies a lot according to humidity, to wood species and to its origin. Furthermore, its large-scale trade is hindered by the high incidence in the transportation cost.⁶ The level of energy dependency of a Country from this type of fuel varies on average from below 3%, in industrialised Countries, to over 40% in developing Countries (with peaks of 70%).

In evaluating the utilisation opportunities and the energy purposes, it is necessary to carefully consider, on a case-by-case basis, the time needed to restore the timber taken from woodlands. In fact, everyone is aware of the *deforestation* and of subsequent *desertification* problems, which are reaching alarming levels globally; however, they are rarely ascribable to energy needs, although they are frequently linked or ascribed to them. It is sufficient to think that the thinning out of plants and the removal of coppices from a wood, provided that it is not excessive, is even beneficial for the wood, since it represents a form a “maintenance” able to favour the renewal of plants and their growth.

Also for biomass in general it is very difficult to exactly quantify their availability and consumption for energy purposes. For instance, it is not possible to estimate precisely and in detail the direct consumption in rural areas (especially in developing Countries) and industrial waste destined to combustion.

Biomass can also originate from the residues of crops expressly destined to the food sector, or from farming activities destined, either totally or partly, to energy production (sugar cane plants, plants rich in starch, etc.), which for this reason are called *energy crops*. High quantities of organic matter can also be derived from self-sown vegetation (wooden material) and from the zootechnical waste of the farms.

Within the European framework of energy use of biomasses, Italy is in a condition of scarce development, despite the high potential at its disposal. In fact,

⁵ Nearly 19,000 kJ/kg for high-quality wood, with 15% in weight of humidity.

⁶ Generally, for distances exceeding 80–100 km the cost of wood becomes higher, given the same energy content, than other conventional sources.

the availability of residual biomasses (wood, farming and agri-food industry residues, urban waste and zootechnical industry) in Italy amounts to nearly 66 million tons of dry matter every year, equivalent to 27 MTOE.

Through a suitable reforestation and forest maintenance programmes, in fact, new biomasses could be available for an annual amount of nearly 2 MTOE. Besides the existing forests, new conventional wood surfaces could be obtained by exploiting part of the over 2,000,000 ha that are not destined to farming due to their low productivity. Furthermore, coppice stands and ground crops mainly destined to energy use could be planted, hence reconverting part of the 250,000 ha that are presently left uncultivated, in compliance with the EU directives enacted in relation to the problem of farm surpluses: the present surface destined to energy crops—extremely limited indeed—should be extended to 3,500–5,000 ha of short-cycle cultivations, but the potential surface amounts to nearly one million ha.

The use of this resource varies according to the origin, the chemical composition (in particular the C/N ratio) and the humidity content. Biomass can be burned directly to obtain thermal energy, or transformed into various types of fuels (biogas or bio-fuels), which improve their quality and usability but lower the level of energy content. In particular, transformation processes aim at producing methane gas compounds with a low or medium calorific value, or other fuel substances (methanol, ethanol, carbon substances, etc.).

As regards the possibility of producing fuels from human waste, it is necessary to consider the potential interest of energy enhancement from municipal solid waste (MSW), a percentage of which is made up of organic matter and which can therefore also be considered as biomass.

2.3.4.1 Overview

Being *every renewable organic matter biomass* is integral to life. This means that biomass is the “fuel” of life, a source of energy and materials.

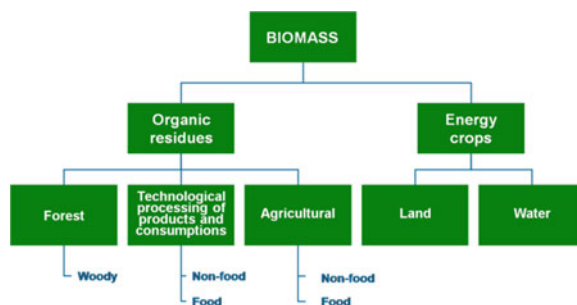
In practice, organic materials (carbon compounds) can be used either “directly” by organisms as their own source of energy and nutrients (in this case, reference is made to *food*) or “indirectly” as a source of external energy or *materials* (clothing, furniture, building, chemicals, etc.).

Thus *food, biomass and renewable materials are strictly connected*. From these preliminary definitions, it is possible to understand the usefulness of *energy-farm* and *bio-refinery*: they propose, respectively, the integrated production of power-food and power-chemicals from biomass.

Biomass has been (and in many cases, in Africa in particular, remains) the first “fuel” of mankind. Today about 11% (around 1,200 MTOE) of total world primary energy supply (nearly 13,200 MTOE) comes from biomass [4].

Biomass is the *fourth primary energy resource worldwide* (following oil, coal and natural gas) although in industrialised Countries it only accounts for 3% of the total, whereas in developing Countries it accounts for 35%, being in many cases the main energy resource. As a matter of fact, a change is occurring in the use of

Fig. 2.18 Biomass typologies



biomass energy from traditional and non-commercial to modern use (high efficiency, high-value energy vectors produced, such as *electricity and bio-fuels*, and integration with industries operating in the food sector or in the field of renewable materials). The transformation as well as the increase in the use of biomass energy are due to the trends explained in the previous chapter on renewable energy sources, and to the potential of energy biomass which is not fully exploited. Therefore, not only the theoretical potential but also the technical and economic ones (that take into account actual technologies and costs) are sometimes higher than actual energy consumption [5].

In brief, biomass is one of the main energy sources available: *the challenge, therefore, resides in its sustainable use and not in its availability*.

As it happens with other energy sources, the use of biomass depends on the global analysis of the production-use system. Different from the other renewable energy sources, biomass—being a fuel (and not a directly convertible energy source, like solar, wind, hydropower and geothermal energy)—is *subject to the traditional energy chain* (and relevant impacts) that provides a “natural” resource to our daily life.

Current energy chains deplete non-renewable resources and release harmful substances, producing waste as well as local and global pollution.

Given that long-lasting development can only exist through the realisation of energy cycles by using renewable energy sources; in this way, the main aim of the energy sector shifts to the so called closed-cycles, and aimed at achieving a “zero-impact” on the environment.

In the case of biomass, the first part of the entire energy chain (extraction and processing) is replaced by growing, harvesting and treatment. Therefore, the entire energy chain encompasses the following steps:

1. *Production* (growing, harvesting and treatment)
2. *Transportation*
3. *Conversion* (and relevant initial and final treatment)
4. *Distribution*
5. *End use*.

Different from the other renewable energy sources, biomass (owing to the large variety of renewable multi-carbon compounds) can be converted through several

Table 2.2 Biomass properties

Property	Range
<i>Proximate analysis</i>	
Humidity content (moisture) (%)	10–70
Calorific value ^a	2–40 MJ/kg (from very wet biomass to very dense oil)
Volatile matter (%)	30–80
Fixed carbon (%)	15–30
Ash (%)	1–10
<i>Ultimate analysis (by weight)</i>	
Cellulose (%)	30–50
Hemi-cellulose (polysaccharides) (%)	20–40
Lignin (%)	5–30
Carbon (%)	40–50
Oxygen (%)	38–43
Hydrogen (%)	5–7
Alkali metal and inorganic element (%)	1–15
<i>Bulk volume (density)</i>	1–50 m ³ /t (daf)
<i>Times of cultivation</i>	6–24 months
<i>Yield (potential annual production capacity)</i>	1–100 (dmt ^b /ha)/yr
<i>Characteristics of cultivation</i>	Depends on climates, land, water, pesticides and fertilisers demand
<i>Production cost</i>	Negative (for waste) to 1 (DC)–5 (IC) €/GJ
<i>Transportation cost</i>	Function of the distance travelled and the energy density (from 0 to 1 MJ/km)
<i>Conditions of suppliers</i>	Depends on local conditions

^a NCV on daf (dry ash-free) basis

^b *dmt* Dry matter tons

processes in order to obtain various products and by-products. From a *chain perspective*, biomass can be divided, as showed in Fig. 2.18, into:

- *Energy crops*: biomass especially planted for energy purposes in marginal or productive land or water.
- *Organic residues*: from woodlands, public parks and gardens, human or animal cultivations, industry (food, wood, textile, ...) or Municipal Solid Waste (MSW).

The former type is subject to the entire chain of biomass, whereas the latter only includes the last three processes (conversion, distribution and end use), if is used in situ.

From a quality point of view, biomass can be divided into

- *Lignocelluloses herbaceous and arboreal plants*, like Miscanthus, poplar, etc.
- *Sugar*, like sugarcane, beetroot, etc.
- *Starch*, such as corn, wheat, etc.
- *Oil* from sunflower, rape, palm, soya, etc.

- *Moisture*: manures, aquatic plants, etc.
- Others.

2.3.4.2 Resource Evaluation

Biomass is characterised by many properties which vary within a wide range (from countries to countries, land, season, management, etc.). In order to use biomass for energy production purposes, all the properties shown in Table 2.2 must be taken into account [5, 6]. Obviously, owing to the very large range of biomass typologies, the value range has to be considered as example (Table 2.2 mainly refers to crops and vegetable residues, the most frequently used biomass).

The first two categories (proximate and ultimate analysis) and the bulk volume show the main chemical and physical biomass proprieties. The moisture content and the cellulose/lignin ratio are of primary concern in the biochemical conversion processes while the moisture, fixed carbon, ash, alkali content and the calorific value are of prime concern in the thermo-chemical conversion processes. The bulk volume is relevant in the transportation and feeding systems (together with the friction and others particular properties).

Times and requirements of cultivation and yield are *general characteristics* of crops. The energy yield (yield and CV multiplied) is the main quantity to consider.

Production and transportation costs are the main *economic characteristics* to take into account. Owing to the large amount needed (the biomass, as shown, has a low energy density) and to the great variability, the *supply conditions* are paramount.

After all, since biomass is a fuel with a large property variety, the possible *variation* of all the related parameters must be analysed. Thus, the biomass energy use implies a careful study of:

- the territory and biomass properties and characteristics
- the *place* where the power plant is setup (not in distant from the biomasses to be used)
- the *reliability* of supplies, conversion technologies, etc.

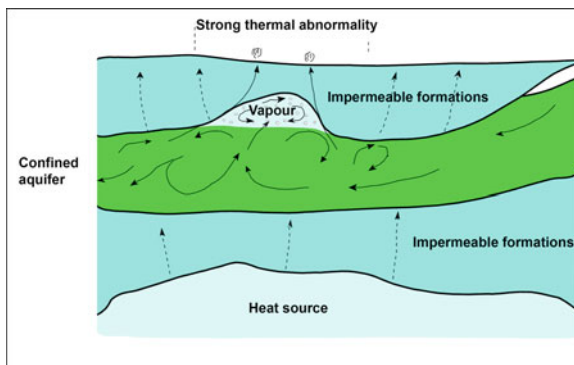
2.3.5 Geothermal

Geothermal energy (from the Greek “gê” and “thermòs”, “heat of the Earth”) is the energy contained inside of the Earth in the form of “heat”.

The origin of this heat relates to the inner nature of our planet and to the physical processes taking place in it.

This heat, although available in huge and practically inexhaustible quantity, is very much dispersed and only rarely concentrated.

Fig. 2.19 Outline of a hydrothermal system



The internal heat regularly dissipates towards the surface of the Earth; its existence can be perceived through the progressive increase of rock temperature as depth increases; the geothermal gradient is, on average, 3°C every 100 m of depth, namely 30°C every km.

Geothermal energy here indicates the exploitable part of natural heat present inside of the Earth's crust. The subsoil of our planet, in fact, shows a thermal gradient linked to the hot nucleus at the core of the Earth according to which temperature increases as depth increases, but mostly to spontaneous radioactivity phenomena, which develop thermal energy locally. The main radioactive elements include Uranium ^{235}U and ^{238}U , Thorium ^{232}Th and Potassium ^{40}K .

Most of the endogenous heat is available at too high depths or in conditions that make it technically impossible to allow its exploitation as energy source. However, there are zones on the surface of our planet whose thermal energy concentration is very high locally (*high thermal areas*). Heat concentration in less deep layers of the Earth's crust, as volcanoes, geysers and hot-water springs, originates the so-called *geothermal systems*; they are effects of natural radioactivity, and not of the gradient.

2.3.5.1 Overview

The only systems presently used on an industrial scale are the so-called *hydro-thermal systems*. They are made up of permeable rocks containing hot fluid (water or steam); named *aquifers*, they are delimited by layers of impermeable rock (Fig. 2.19).

The feeding of aquifers, which can be considered as natural reservoirs, is due to the introduction of meteoric water—that is to say coming from atmospheric precipitations—through the recharging surfaces, formed by zones where the reservoir itself comes to surface. *The heat that warms the fluid is provided by the natural decay of isotopes within the Earth*; the particles emitted by the basins of radioactive material are, in fact, slackened by the surrounding masses, converting their kinetic energy into heat.

Some necessary conditions (although not sufficient) must be assessed for the existence of hydrothermal systems. They include the *presence of a heat source at a suitable temperature* (at least 600°C) at a not too high depth; the *presence of permeable rocks*, making up the aquifer, and *impermeable rocks*; and the suitable renewal, in the subsoil, of *meteoric water*. In general, the renewal is guaranteed by the fact that meteoric waters, while warming up, undergo a pressure increase and often turn into vapour, hence tending to raise through either natural or artificial shafts. The hollow deriving from this process is filled with other meteoric water that, through its infiltration in the ground, feeds the cycle. The upper impermeable layer guarantees a suitable pressure and reduces the thermal flow towards the surface.

According to geological and thermodynamic conditions, the endogenous fluid can appear at the shaft outlet in three different ways: *in liquid phase*, as *saturated vapour* (low enthalpy), or *superheated vapour* (high enthalpy). In case of presence of high quantity of vapour, the hydrothermal system is defined as *vapour-dominated*; in case of presence of liquid and low quantity of vapour, a *water-dominated* system takes place.

All the reservoirs contain, in variable percentages, incondensable minerals and gases, mainly formed by carbon dioxide.

Presently, most of the electric energy produced from geothermal energy is based upon high-enthalpy sources, although there are already several applications using saturated vapour and even hot water.

Non-hydrothermal systems are represented by the so-called *hot dry rocks* and by *magmatic systems*.

The *former* are highly-thermal zones of the Earth's crust, although free from aquifers, therefore lacking in a vector transporting heat to the surface. In order to exploit this energy source, it is possible to cause, through artificial fracturing, a forced circulation of endogenous fluid.

Magmatic systems are made up of high-temperature fused rocks (magma) and entail huge difficulties in terms of energy extraction; the possibility of their exploitation is remote even if recently innovative energy systems have been proposed.

The *disadvantages* relating to the use of geothermal energy are mostly linked to the *uncertainty of its finding and of the consistency* of the source, as well as the *high extraction costs*. Huge investments are needed for the more and more difficult determination of exploitable zones and for shaft drilling. Before its use, the fluid coming from the subsoil always has to be processed since it contains, as already said, gases, minerals and dissolved water (in case of vapour-dominated systems), which are harmful both for the conversion plants and for human health.

2.3.5.2 Resource Evaluation

The world distribution of geothermal sources sees a concentration in the zones of contact between tectonic plates, where the earth's thermal gradient is higher due to

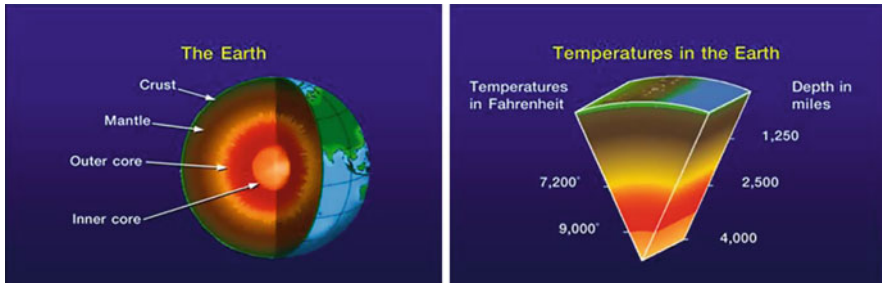


Fig. 2.20 Earth layers and relevant temperatures

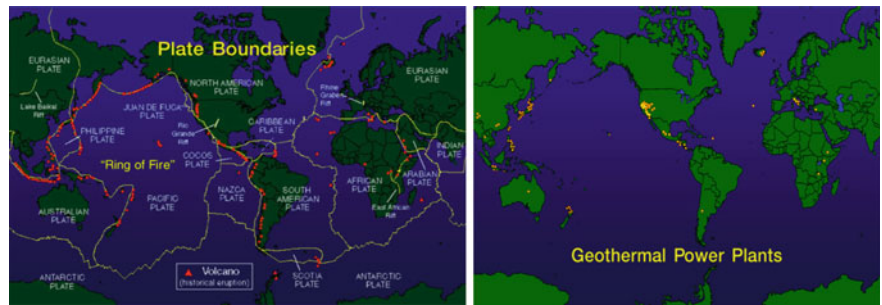


Fig. 2.21 Plate boundaries and geothermal power plants

Fig. 2.22 Geothermal phenomena



the fractures of superficial layers; some of these zones are traditionally called “volcanic zones” (Fig. 2.21).

Globally, the first experiments entailing the industrial exploitation of geothermics were performed in Larderello (Tuscany, Italy) in 1904, whereas the first geothermal power station (with a power of 250 kW) was established in the same area in 1913.

Having considered that the word *geothermal* comes from the Greek *gea* (Earth) and *thermos* (heat), geothermal energy is usually defined as the heat stored within the Earth. Heat originates from the Earth’s molten interior and from the decay of radioactive materials. Its quantity is larger than the solar energy theoretical potential (the annual solar radiation). In fact, not only the total geothermal

theoretical potential is more than 100,000 times higher than the world's energy consumption, but also its smaller total technical potential (about 5×10^{12} GJ) is higher than the world's energy consumption (about 45×10^9 GJ), despite an actual use of about 2×10^9 GJ. However, like other renewable sources (solar energy, wind energy), geothermal energy is widely dispersed. Consequently, the technological ability to use geothermal energy will determine its future spreading.

The Earth has four main layers, and each layer has different compositions, functions and temperatures, as is shown in Fig. 2.20.

The crust is the outermost layer of the Earth, the land that forms continents and ocean floors. It can be from 3 to 8 km thick under the oceans and from 25 to 55 km thick on the continents.

As a matter of fact, the heat of the Earth dissipates towards its surface in a way that leads the Earth's temperature to increase by nearly 3°C every 100 m of depth, being therefore a difference in temperature too low to generate a great local power. However, the Earth's crust is broken into pieces called *plates*; magma therefore comes close to the Earth's surface, near the edges of these plates. Consequently, geothermal energy is generally greater in areas where tectonic plates collide and generate volcanic activity, as it can be seen in Fig. 2.21, which shows where plate boundaries and geothermal power plants are located. For example the Pacific ring (ring of fire) is a prime spot for the harnessing of geothermal activity because it is an area where tectonic processes are always taking place.

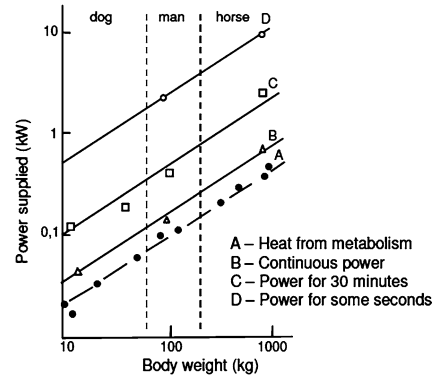
Even if most geothermal reservoirs are deep underground with no visible clues showing above ground, the geothermal energy can sometimes find its way to the surface in the form of *volcanoes* and *fumaroles* (holes where volcanic gases and vapour are released), *hot springs* and *geysers* as shown in Fig. 2.22.

When magma comes close to the surface, it heats the ground water trapped in porous rock or water running along fractured rock surfaces, and faults. These features are called hydrothermal and have two common ingredients: water (hydro) and heat (thermal). Thus, water at high temperatures (300°C) can also be available for many applications. Large areas with hydrothermal resources are called *geothermal reservoirs*. Therefore, four types of geothermal energy are usually identified:

- *Hydrothermal* hot water or steam at moderate depths (0.1–4.5 km).
- *Geopressed* hot-water aquifers containing dissolved methane under high pressure, 3–6 km depth.
- *Hot dry rock* abnormally hot geologic formations with little or no water.
- *Magma* molten rock at temperatures of 700–1,200°C.

Today only hydrothermal resources are used on a commercial scale for electricity generation and as a direct heat source. These four types of geothermal energy located in particular areas have to be added to the use of Earth's stable ground or water temperatures near the Earth's surface; therefore, it is possible to take advantage of the relatively constant temperature of the core of the Earth, using it for both heating and cooling purposes. Moreover this source of energy is available everywhere.

Fig. 2.23 Total power provided by different living beings according to their weight



Since some renewable energy sources can only operate under favourable weather conditions, they are often considered as limited in their ability to meet the looming large-scale power needs of the 21st century. However, geothermal energy, has the potential to provide reliable electricity sources while still offering significantly lower emission levels than fossil fuels, as well as avoiding problems in terms of radioactive waste disposal. Geothermal relies on a readily available, constant source of heat for generation, and is therefore considered a base-load resource. A base-load resource operates most efficiently at a relatively constant level of generation, and is not limited by changes in weather conditions or other factors. The *availability factor* is measured as the number of hours that a power plant is available to produce power divided by the total hours in a given period of time, usually 1 year. Geothermal energy *availability factor* is about 95%. This means that geothermal power plants are available for generation 95 % of any given time, based on decades of observations by plant operators. While availability factor measures a plant potential for use, the *capacity factor* measures the amount of real time during which a facility is used. A Geothermal plant also has a great capacity ranging from 89 to 97%, depending upon the type of geothermal system in place.

2.3.6 Other

2.3.6.1 Human and Animal Power

Since the prehistory, human beings learned how to use animal energy, besides human energy, for the individual and social needs of their community. Still nowadays, in many developing countries, this energy resource is among the most common and widespread energy sources, also because very often it is the only one easily and conveniently available.

The size of this source varies according to the animal providing energy and, different from almost all the other sources, from the duration of the period in which the effort is provided; in this case, then, it is more suitable to refer to the available

power. Figure 2.23 shows some power values according to the weight of the animal involved.

The analysis of human and animal energy lies outside of the purposes of this research; however, it has to be taken into consideration, not only in relation to the situation of some Countries that largely use it still nowadays, but also as a basis of comparison of any energy system.

2.3.6.2 OTEC

The *Ocean Thermal Energy Conversion* (OTEC) is the technology that exploits the heat stored in oceans to generate electricity. In order to allow an OTEC plant to produce a suitable quantity of energy, it has to be installed where the difference in temperature between hot surface waters and cold deep waters amounts to nearly 20°C. These conditions are identified in the coastal areas of the tropical seas between the Tropic of Capricorn and the Tropic of Cancer.

2.3.6.3 Tidal Power

Cyclic phenomenon extended to the entire hydrosphere and generated by the pull of the moon and of the Sun on bodies of water. *Tidal excursion* is the tidal range between the two limits of high and low water (*intertidal height*).

Depending on the positions of the moon and of the sun, the higher high water occurs after the phases of full moon and new moon, and is named *springtide*, whereas the lower low water occurs after moon quarters and is called *neap tide*. According to the size and the geometry of the sea and ocean basins involved in the passage of the tide, the tidal stream can reach remarkable levels of flow and velocity. A tide gauge is installed in water for the measurement and recording of tidal range.

Energy can be derived from the regular lowering and increasing of water bodies. To build a tidal plant, an estuary must be dammed towards the sea with an artificial dam. The energy technique exploits tidal excursion (the high-water and low-water range). A sufficient tidal excursion, as it happens in Northern France, at St. Mâlo, where the difference between the lower and higher water is around 12–13 m.

Tidal power plants; however, have the disadvantage that their maximum yield daily shifts by nearly 50 min with the rhythm of the tides. The optimal conditions for tidal power plants are rarely met. Besides St. Mâlo, small devices are operating on the banks of the White Sea in Russia, in Scotland and in China.

2.3.6.4 Wave Energy

Wave energy can be exploited in different ways for the production of electric energy. The main ones are the following:

Table 2.3 Summary of the RES potential in EJ/y [7]

Resource	Current	Share (%)	Technical Potential	Share (%)	Theoretical potential	Share (%)
Biomass	48.3	79.3103	276	3.6600	2,900	0.0002
Hydro	10.0	16.4204	50	0.6630	147	0.0001
Solar power	0.2	0.3284	1,575	20.8858	3,900,000	2.7100
Wind power	0.3	0.4926	640	8.4869	6,000	0.0042
Geothermal power	2.1	3.4483	5,000	66.3042	140,000,000	97.2837
Total	60.9	100.0000	7,541	100.0000	143,909,047	100.0000

- *Waves are directed towards a concrete chamber* the increase in water level compresses the air inside of the chamber that activates a turbine. Also the depression during wave return is exploited to activate the turbine.
- *The vertical motion of waves moves a piston* designed as a floating body.
- *A collection tunnel lifts waves for several metres* and lets them fall on a turbine.

2.3.6.5 Sea Currents

The kinetic energy of sea currents can be successfully exploited. Indicating with Q the volume flow rate (m^3/s), with ρ seawater density (kg/m^3), with A the passage section of sea current (m^2) and with V current velocity (m/s) the power available (W) is:

$$P = \frac{1}{2} \rho \cdot Q \cdot V^2 = \frac{1}{2} A \cdot \rho \cdot V^3 \quad (2.21)$$

Considering a unit section ($A = 1 \text{ m}^2$) and assuming $\rho = 1.000 \text{ kg}/\text{m}^3$, (2.21) becomes:

$$P = 500 \cdot V^3 \quad (2.22)$$

From the economic point of view, this resource is exploitable if the power available is not lower than $500 \text{ W}/\text{m}^2$. Equation 2.22 shows therefore a minimum current velocity of $1 \text{ m}/\text{s}$.

2.3.7 Current Renewable Energy Use

The current use of RES is about 10% of world energy consumption, but the theoretical and technical potential of renewable energy is huge and it is mainly due to solar and geothermal energy (Table 2.3). In fact, only about 0.02% of global

contribution to the Earth energy balance⁷ does not come from solar energy, but rather from geothermal, gravitational and nuclear energy. Moreover, the technical potential of solar indirect power (wind, hydro, biomass, wave) are about half or one-third (depending on individual evaluations) of solar direct technical potential. Geothermal energy theoretical potential originates from the Earth's molten interior and from the decay of radioactive materials; its quantity is larger than the solar energy theoretical potential (the annual solar radiation). In short, not only the total theoretical potential is 100,000 times higher than world energy consumption (geothermal 100,000, solar 10,000, and the rest about 10),⁸ but also the total technical potential of RES is 20 times higher. Therefore, its implementation mainly depends on technological capacity and costs, not on availability. Therefore, in consideration of the huge unexploited potential, perspectives are very interesting; it is necessary to take into account the expected capacity, efficiency, as well as economic, social and environmental impacts.

If for large hydropower and geothermal plants it is difficult to foresee technological improvements, thermal solar power plants can only be considered in a future perspective (in fact, exception made for some pilot plants and projects, there are no commercial power plant). For mini-hydropower, wind and photovoltaic power, an efficiency increase can be foreseen (and a cost decrease of 10 and 50%, respectively). The same considerations apply for bio-energy systems, but in this case improvements are linked to an increase in annual hours of operation (i.e., from 5,000 to 7,000).

2.4 Non-renewable Energy Sources

Energy sources with a well-established position in world trade, and underlying economic relations and balances, as well as energy trade between different Countries, are generally referred to as *conventional* (or *commercial*) energy sources: these are mainly non-renewable sources. Their real availability, the long-term predictability of price levels and the impact on the environment produced by the operating cycle (finding, transportation, utilisation and disposal of residues or waste) evidently are critical problems for the political, socio-economic and environmental sustainability of the use of these sources.

Availability depends on several factors of physical, technological, economic-financial and geopolitical nature. Once a deposit—or a primary energy source—is

⁷ The Earth is a physical open system (exchange only energy no matter) so, normally, receives energy from the Sun and returns almost the same energy quantity to maintain its average temperature.

⁸ From the mean average value of *annual* solar constant (1.37 kW/m^2) and the mean radiate terrestrial surface, it is possible to calculate a terrestrial annual solar irradiation of about $5.44 \times 10^{24} \text{ J}$ ($1.370 \text{ W/m}^2 \times 1.27 \times 10^{14} \text{ m}^2 \times 3.600 \text{ J/W} \times 24 \times 365$) against an annual primary energy consumption of about $550 \times 10^{18} \text{ J} = 550 \text{ EJ}$ (1 oil kg has $10,000 \text{ kcal} = 4.1868 \times 10^7 \text{ J}$; thus $1 \text{ Gtoe} = 4.1868 \times 10^{19} \text{ J} = 41.868 \text{ EJ}$).

Table 2.4 Main features of the different types of coal

	Humidity (%)	Ashes (%)	HCV (kcal/kg) ^a	Volatile substances (%)
Peat	—	—	5,500	—
Lignite	20–35	15–30	7,200	—
Bituminous coal	5–15	10–20	7,200	12
Anthracite	5–8	10–35	7,700	12

^a The calorific value is referred to pure fuel, free from ashes and humidity

identified, the suitable technological devices to stock up at the minimum possible costs are needed; subsequently, the primary energy obtained has to be eventually processed by transforming or converting it into an adequate energy vector, which finally has to be transported to end users. All this requires know-how, investments and organisation.

The “energy issue” overwhelmingly came to the fore at the beginning of the 1970s, mainly as an international political issue: it became evident, in fact, that the business chain had a weak link in the relations between oil consuming Countries (mainly industrialised Countries), and oil exporting Countries (mainly developing Countries, mostly in the Arab Middle East).

However, there are also objective physical factors that influence the availability of conventional energy and, in particular, fossil energy. Being “non-renewable”, these sources are destined to deplete, although in the medium-long term, since the time needed for their replenishment is largely higher (even millions of years) than the time of their consumption, amounting to tens or hundreds of years.

Additionally, availability also depends on the good value for money relating to the exploitation of each deposit. Very often, the so-called “*available resources*” are not used since their marketing and trade is not cost-effective: many deposits, although localised long time ago, are still unexploited since their extraction costs and transportation charges are too high. Therefore, depending on market prices and available technologies, a distinction is made between *economically extractable reserves* and *potentially extractable reserves*, being clear what these definitions refer to.

Among the causes for additional costs in the exploitation of energy sources, it is also necessary to consider the presence of technological and environmental constraints. The environmental impact, in fact, is the other critical factor for the use of conventional sources.

The case of coal is emblematic: in its entire cycle—from its production to its energy use—it is responsible for various forms of pollution. Thereby, mining activities, either underground or open-cast, cause different types of environmental problems with complex solutions, also linked—among other things—to the safeguard of workers’ health and of the environment in general. On the other hand, open-cast mines—that are much more productive—very often have a non-sustainable environmental impact on the areas involved, causing the disruption of the social, agricultural, hydrological and economic fabric. Additionally, the problems related to transportation, combustion and, last but not least, ash disposal, must be considered.

In general, each commercial energy source is indissolubly linked to an environmental impact cycle, more or less critical and dangerous.

2.4.1 Coal

2.4.1.1 Definition and Structure

Coal, or better, *hard coals* are solid mineral substances and, from the energy viewpoint, represent the most important and abundant class of natural solid fuels.

Traditionally, coal is divided into four categories:

- *Peat*
- *Lignite*
- *Bituminous coal*
- *Anthracite*

Out of them, only *bituminous coal* and *anthracite* represent proper coal. Table 2.4 shows some pieces of data on the main features of coal according to this subdivision.

These values shall be considered as indicative of different categories that are not however strictly differentiated.

As to its structural features, coal is made up of a large variety of macromolecules,⁹ very much different in terms of weight, although; however, sharing a common lamellar morphology.

In each macromolecule two areas can be identified; the *condensation nucleus* of aromatic rings, whose size characterises the *carbonisation degree*,¹⁰ and one *peripheral area*, made up of different types of functional groups, which characterise the molecule itself.

The total percentage of carbon depends on the degree of transformation achieved, and ranges from 55 to 95% (on the dry substance); the uncombined portion (aromatic nuclei) ranges from 20 to 90%.

2.4.1.2 Genesis of Coal

The processes that led to the formation of fossil fuels are still analysed nowadays, although it is considered as clearly determined that the different types of coal share a sedimentary and phytogenic origin. In fact, it is certain that, starting from the paleozoic age,¹¹ huge quantities of organic matter, mainly of vegetable origin,

⁹ These are mainly high-molecular mass carbon compounds with hydrogen and oxygen, containing, in minor percentages, nitrogen, phosphorus and sulphur.

¹⁰ From the chemical viewpoint, *carbonisation* consists of a process that increases the size of the aromatic nucleus and increases its condensation; the latter inversely depends from the quantity of non-aromatic bridges that connect aromatic rings.

¹¹ More precisely, one of the periods of the Paleozoic era, which goes from 570 to 225 million years ago. It is the *Carboniferous* period, which began nearly 350 million years ago and takes its name from this important phenomenon.

were accumulated in wet environments, originating a process of carbon enrichment (*carbonisation*). This circumstance is also demonstrated, among other things, by the finds of vegetable organic remains¹² in less evolved coal-beds.

To clarify the topic of coal genesis, it is necessary to take into consideration at least the main factors that, more or less directly, have caused it; among them, the types of vegetables transformed, the geological and environmental conditions and chemical–physical phenomena.

The paleobotanic studies carried out on hard coals demonstrated how the biological nature of vegetable combinations, which underwent fossilisation in the carboniferous Age is rather similar to the nature of the plants that nowadays grow in marshes and in the lagoons of equatorial regions with hot-wet climate. The reason why the main coal basins are, on the contrary, almost all included in the temperate climate area has to be ascribed to the fact that the territories in the intertropical area underwent, in the areas following the Paleozoic Age, a series of slips on the Earth surface,¹³ that determined its present position.

Coal deposits typically have a configuration with repeated layers or seams,¹⁴ each one with a constant or gradually variable thickness, whereas the rocks associated and alternate to coal-beds are generally sedimentary (calcareous, sandstone, etc.), sometimes of sea origin. Furthermore, it is possible to observe that the different layers have a marked parallelism: it is possible to infer that the arboreal organisms growing in marshy areas, or in any case in flat lands, were periodically flooded and covered by the sea, due to local bradyseisms, originated in this way vegetable organic sedimentations. Each time they were covered by inorganic sedimentations, originated in this way the stratigraphic alternation between hard coal and sedimentary rock. This also explains the existence of thick coal-beds,¹⁵ which probably represent the result of the deposit of vegetable substances in subsequent stages, each time on pre-existing material of the same nature but already partly transformed.

Apart from the indications suggested by the growing percentage of carbon, the fact that neither peat-beds were ever found below lignite deposits, nor layers of lignite below bituminous coal and anthracite beds, shows that the process occurred in this sequence: peat, lignite, bituminous coal and anthracite.

As to the chemical-physical processes involved in coal formation, two phases can be identified, although there is no sharp separation between them.

At the beginning, *biochemical factors* are involved. Fermentative and putrefactive changes of the organic matter take place in an acid environment ($\text{pH} < 7$); they are caused by *aerobic bacteria* and fungi, which consume oxygen and are

¹² Mainly leaves, stems, seeds and, sometimes, carbonised trunks that perpendicularly cross coal layers and that still have roots in the ground underlying the bank.

¹³ This is in line with the hypothesis made by Alfred Wegener, in his continental drift theory (1915), and confirmed by more recent studies that led to the formulation of the plate tectonics theory.

¹⁴ In northern French–Belgian basin there are up to 400 coal-beds of a thickness of 2,000 m.

¹⁵ The thickest bank known is the one of the Kommentry basin, in central France that in some points exceeds 24 m of thickness.

only available at depths lower than 40 cm. Vegetable materials decompose quickly, and the main chemical reactions include oxidation and hydrolysis; a part of carbon is disposed from the vegetable matter (in the form of carbon dioxide and carbon monoxide), but most of it is kept, and its percentage compared to the other elements increases.

Subsequently, at higher depths, in the absence of oxygen and with pH close to neutral, *anaerobic bacteria* intervene. They survive in the absence of oxygen, and determine a further decomposition of materials—much slower than the previous one—as well as the formation of humic acid or humus¹⁶ through chemical reactions, mainly involving reduction and hydrolysis.

With the gradual sinking of humic deposits, the conditions allowing the lives of fungi and bacteria disappear; in this way, the second phase of transformation begins; it is a merely inorganic phase, involving factors as time, pressure and temperature.

Time only partly influences the entire process; this is highlighted, for instance, by the limited degree of transformation achieved by the coal of a basin identified near Moscow, whose age dates back to the Carboniferous period, that is to say the same period to which date back coals with the highest degree of transformation. In this deposit, a concomitance of other conditions unfavourable to carbonisation occurred. However, in general the most ancient carboniferous formations, given the same other conditions, are more evolved and richer in carbon than recent ones.

Also the pressure due to the load exercised by the overburden is not a particularly relevant cause of the carbonisation process; at the most, this compression may impact on coal porosity. Not even more powerful pressures due to tectonic movements can be considered as directly influencing metamorphosis processes; according to a widespread opinion, the carbonisation of the main basins on the Earth was already completed when, in the Mesozoic Age, the drift of plate tectonics on the earth surface began.

Temperature is therefore the key factor in the carbonisation process. In consideration of the thermal gradient of the earth, amounting on average to nearly 3°C every 100 m of depth, and of powerful magmatic intrusions contiguous to the beds of humic deposits, it is believed that the latter—that in the carboniferous period were covered by large layers of sedimentary rocks—might have reached temperatures close to 200°C, sufficient to guarantee the conditions for the carrying out of the metamorphosis process.

2.4.1.3 Physical Characteristics and Technological Merits

The relationship between the chemical composition and the technological features of coal is rather complex; for this reason, it is preferable to directly take into

¹⁶ Complex material, of vegetable origin, mainly made up of carbon.

consideration the parameters characterising fuels according to the different usages they are destined to.

The most frequent evaluations, then, include *the measurement of the calorific value, the immediate analysis, fuel behaviour after heating, and sulphur analysis*.

The *measurement of the calorific value* is made experimentally, mainly through the use of calorimeters. The calculation is obviously referred to the lower heating value, since all fuels contain a given quantity of water,¹⁷ called *fuel humidity*; when fuels burn, water vapourises at the expense of part of the heat generated.

The value of the moisture degree is one of the determinations of the *immediate analysis*. The other tests of this analysis consist in the evaluation of *ashes*, for which it is important to know the quantity produced during combustion, and the melting point; in this case as well, it is necessary to resort to experimental determinations. The determination of *volatile substances* and of *coke*¹⁸ follow, as they are useful to trace back the type of coal examined and the energy use that can be done of it. In this connection, a few distinctions are made among fossil fuels in relation to the result of these tests. For instance, a coal characterised by a high content in volatile substances will be defined as *cannel coal*, in relation to the particular combustion developed; otherwise, the coal in question will be *blind coal*.

The analysis of *burning coal behaviour* is important to make a distinction between coals that burn completely, remaining in an incoherent state, and those that, if warmed, inflate and hinder the passage of air. The latter phenomenon is quantified through a suitable *swelling index*. As regards *sulphur*, finally, it can be found in coal under the form of organic compounds, or of sulphides and sulphates.

2.4.1.4 Composition and Classification

The subdivision introduced in [Sect. 2.4.1.1](#), according to which coals are divided into peat, lignite, bituminous coal and anthracite is not sufficient to rigorously identify the possible energy use.

The classifications adopted for commercial purposes, in fact, were drafted without any reference to univocal and rigorous criteria. This also for the evident purpose by each producing country to use parameters that better highlight and enhance the characteristics of the coals extracted in their own basins. In any case, these classifications are based on the content of volatile matter and, secondarily, on calorific value.

¹⁷ Part of water is also formed during combustion.

¹⁸ Coke is the solid residue left after coal warming at 1,000–1,100°C without air, once it lost its volatile substances—either pre-existing or which formed during warming. This material is hard, porous, grayish, with metallic nuances, and is endowed with a high calorific value (up to 7,400 kcal/kg).

In 1949 the United Nations Economic Commission for Europe established an *ad hoc* Committee entrusted with the task of drafting an international classification through which setting the different types of coal, irrespective of their origin. The works were completed in 1956; according to this classification, each coal is characterised by a *three-digit code*, each digit indicating a *class*, a *group* and a *subgroup*, respectively.

In total, 10 classes were identified, which indicate the content in volatile matter; whenever this value exceeds 33%, the higher heating value is introduced as a discriminating value. The groups and subgroups, amounting to four and six, respectively, are determined on the basis of other properties as, i.e., the swelling index and the agglomerating power.¹⁹

Another important classification is made by ASTM²⁰ (Specification ASTM D-388) according to which coals are divided into *four classes*:

- *Anthracite*
- *Bituminous*
- *Sub-bituminous*
- *Lignite*

Classes are in turn divided into *groups*, which are characterised by the content in fixed carbon,²¹ by the quantity of volatile matter,²² by the higher heating value and, subordinately, by the agglomerating power.

2.4.1.5 Treatment and Use

In order to improve the collection, transportation and combustion of coal, many researches were carried out. The main hindrance is represented by its *lack of fluidity*—for this reason coal needs expensive transportation infrastructures—linked to the high rate of emissions of polluting substances that need fumes abatement systems, in this case as well entailing outstanding economic commitments.

Various technologies were developed in the attempt of giving coal those peculiar characteristics that allowed oil and natural gas to gain ground in recent times (removing in this way the two “negative” characteristics of solidity and highly polluting combustion):

- *Pulverisation*: presently, this is the most developed and widely used technique in the industrial sector. It allows to burn in steam generators the coal dust injected thanks to the suitable fans. Among its main problems: the easiness of

¹⁹ Coal capacity to agglomerate inert substances.

²⁰ American Society for Testing and Materials.

²¹ Solid residue obtained through distillation and determined with normalized methods without considering ashes.

²² They represent the *portion transformable into gas through warming* and is determined by heating the fuel inside of a closed oven filled with inert material for a given time and at a predetermined temperature.

self-combustion in deposits and the possible environmental impact in the transportation and storage phase.

- *Gasification and liquefaction*: they entail the addition of hydrogen (through steam) to coal, which in this way becomes a hydrocarbon. The energy necessary for the separation of hydrogen from water shall be provided by coal itself, in order to have a positive economic balance in this operation. Synthetic gas is obtained ($\text{CO} + \text{H}_2$) which may be further modified by adding steam in order to have a quantity of hydrogen exceeding the amount necessary to convert coal into hydrocarbons.

Some of the processes used and/or under study include:

- Hydrocarbonisation
- Hydrogenation
- Extraction
- Fischer–Tropsch process²³
- *Coal–oil*: mix of oil and coal dust (all included in the combustion chamber).
- *Coal–water*: creation of an inhomogeneous mix of water and coal particles (not all included in the combustion chamber: need for further links in the technological chain, increasing costs).

2.4.1.6 Reserves and Geographical Distribution

Among fossil fuels, coal is undoubtedly the one that offers more guarantees in terms of future supplies, thanks the huge reserves identified, as shown in Table 2.5.

On the basis of present production and consumption rates, the estimated availability of coal apparently ensures stocks for the next 133 years (Fig. 2.24). This estimate, however, is not entirely exhaustive, first of all because the level of coal exploitation is strictly connected to the other commercial sources, mainly oil and natural gas, whose depletion is expected to occur far earlier. Furthermore, it is necessary to take into consideration the uncertainty in the determination of economically usable reserves, which change according to the variations in market prices.

The localisation of world reserves sees coal sufficiently available in all geopolitical areas; however, a particular concentration is present in North America (29.6%), in ex-URSS (26.7%) and in China (13.5%), as shown in Fig. 2.25.

²³ *Fischer–Tropsch process*: method for the synthesis of hydrocarbons and other aliphatic compounds. Synthetic gas, a mixture of hydrogen and carbon monoxide, is reacted in the presence of an iron or cobalt catalyst; much heat is evolved, and such products as methane, synthetic gasoline and waxes, and alcohols are made, with water or carbon dioxide produced as a by-product. An important source of the hydrogen–carbon monoxide gas mixture is the gasification of coal (see *water gas*). The process is named after F. Fischer and H. Tropsch, the German coal researchers who proposed it in 1923.

Table 2.5 World coal reserves at the end of 2007, in million tons [7]

	Anthracite and bituminous	Sub-bituminous and lignite	Total	%
USA	112,261	130,460	242,721	28.6
Canada	3,471	3,107	6,578	0.8
Mexico	860	351	1,211	0.1
<i>Total North America</i>	116,592	133,918	250,510	29.6
Brazil	–	7,068	7,068	0.8
Colombia	6,578	381	6,959	0.8
Venezuela	479	–	479	0.1
Others	172	1,598	1,770	0.2
<i>Total Central America</i>	7,229	9,047	16,276	1.9
Bulgaria	5	1,991	1,996	0.2
Czech Republic	1,673	2,828	4,501	0.5
Germany	152	6,556	6,708	0.8
Greece	–	3,900	3,900	0.5
Hungary	199	3,103	3,302	0.4
Kazakhstan	28,170	3,130	31,300	3.7
Poland	6,012	1,490	7,502	0.9
Romania	12	410	422	0.0
Russia	49,088	107,922	157,010	18.5
Spain	200	330	530	0.1
Turkey	–	1,814	1,814	0.2
Ukraine	15,351	18,522	33,873	4.0
UK	155	–	155	0.0
Others	1,025	18,208	19,233	2.3
<i>Total Europe and Eurasia</i>	102,042	170,204	272,246	32.1
South Africa	48,000	–	48,000	5.7
Zimbabwe	502	–	502	0.1
Other Africa	929	174	1,103	0.1
Middle East	1,386	–	1,386	0.2
<i>Total Africa and Middle East</i>	50,817	174	50,991	6.0
Australia	37,100	39,500	76,600	9.0
China	62,200	52,300	114,500	13.5
India	52,240	4,258	56,498	6.7
Indonesia	1,721	2,607	4,328	0.5
Japan	355	–	355	0.0
New Zealand	33	538	571	0.1
North Korea	300	300	600	0.1
Pakistan	1	1,981	1,982	0.2
South Korea	–	135	135	0.0
Thailand	–	1,354	1,354	0.2
Vietnam	150	–	150	0.0
Other Asia-Pacific	155	276	431	0.1
<i>Total Asia-Pacific</i>	154,255	103,249	257,504	30.4
<i>Total</i>	430,935	416,592	847,527	100

Fig. 2.24 Coal consumption/production ratio

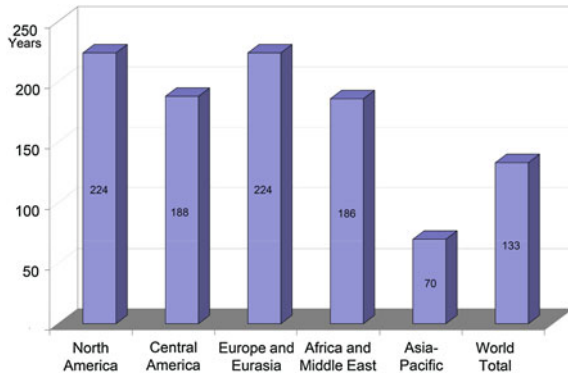
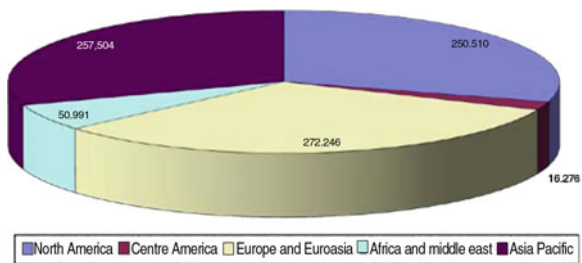


Fig. 2.25 World distribution of coal reserves



2.4.2 Oil

2.4.2.1 Definition and Structure

The word *petroleum* derives from the two Latin words *petra* and *oleum* that is, to say “stone oil” and, in its general use, it indicates an oily liquid, with a variable density, brown in colour with yellow or fluorescent black shades, insoluble in water. The scientific and technical meaning is wider and includes *all natural mixtures mainly made up of hydrocarbons*,²⁴ *being either liquid or gaseous or solid*; in this framework, liquid oil (at room conditions) is called *fuel oil* and the gaseous one is called *natural gas*.

Petroleum is the primary energy source presently most used all over the world. The reasons for this spreading are mainly linked to its relatively *high energy density* (on average 10,000 kcal/kg that is around 41,860 kJ/kg), its considerable *chemical–physical stability* and the *limited quantity of solid residues* produced with its combustion. Furthermore, since petroleum is liquid at its normal

²⁴ *Hydrocarbons* are, by definition, exclusively made up of hydrogen and carbon; strictly speaking, then, the word “hydrocarbons” shall not be used as a synonym of petroleum, since it contains, in lower percentages, other organic compounds made up—besides hydrogen and carbon—by nitrogen, sulphur, oxygen and other elements.

conditions in the environment, it can be *transported relatively inexpensively*; given the same calories transported, it is certainly preferable over both natural gas (aeriform) and coal (solid).

The main disadvantages of this strategic source, which have caused its enduring crisis in the last decades, are linked to the fact that it is characterised by a *geopolitically unbalanced distribution*, it is a *non-renewable* source and its combustion produces a *remarkable air pollution*.

In some cases, petroleum may spontaneously reach the earth surface and burst into flames for natural causes; this is how men learned about its existence since the prehistory. Already around 3000 BC, in Mesopotamia, *bitumen* (i.e. thick and oxidized oil) was used as a fuel for lighting, as a binder in the building sector, for the waterproofing of the hulls of boats, or as a preservative for wood and leather, and as a medicine. There are also witnesses indicating the research and extraction of petroleum in the subsoil, through artificial wells, in China as from 250 AD.

In any case, the official date of the beginning of the modern oil industry traditionally dates back to 1859, when the US colonel Drake was entrusted with the task of performing drilling at Oil Creek, in Pennsylvania, with the specific purpose of finding petroleum.

From the morphological viewpoint, its structure is made up of a mix of different hydrocarbons and, to a lower extent, of other organic substances. It is not possible to perform a complete classification of all its components, since they more or less amount to over one thousand; for instance, the American Petroleum Institute (API) has identified 350 different types of hydrocarbons, almost all liquid. The fluctuations of weight percentage values of the main elements include the following:

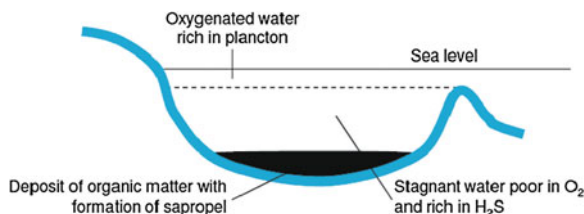
- C: 83–87%
- H: 11–15%
- O: 0.05–4%
- S: 0.05–7%
- N: 0.05–2%

2.4.2.2 Genesis of Oil

An *oil field*, that is to say the reservoir in which oil is concentrated in such quantities that make its extraction cost-effective, is the final result of a very slow process that determines petroleum formation and, generally, its migration from the place of origin to the place of storage, which are often far from one another. Because of the particular complexity and duration of this process, its phases have not been, until today, sufficiently clarified, although in the last few years satisfactory progresses were obtained, especially in the field of geochemical research.

In the past, the origin of petroleum was ascribed to *the combined action of pressure and temperature on the remains of crustaceans, molluscs and, in any case, large animals* (both sea and terrestrial animals); present hypothesis, on the contrary, indicate that the initial organic matter originated from sea settlements of

Fig. 2.26 Area of deposit of oil organic substances



micro-flora and micro-fauna. The *organic origin of petroleum*²⁵ is in any case ascertained on the basis of some objective elements. For instance, a large quantity of organic matter can be observed in the sedimentary rocks rich in carbon and hydrogen, which are particularly suitable for oil formation; it is also possible to assess that all types of petroleum contain nitrogen and porphyrin pigments of exclusively vegetable and animal origin. Porphyrin, in fact, can derive from both vegetable chlorophyll and from animal haemoglobin. Nitrogen, conversely, varies in sediments directly proportionally to organic carbon.

Animal and vegetable microorganisms, once dead, accumulate at the bottom of aquatic basins, together with small siliceous, calcareous and argillaceous particles, transported as detritus by watercourses and by the wind. The deposit of these sediments takes place in particular in smooth and shallow waters as, for instance, in gulfs, inland seas and lagoons, and it is what still nowadays forms the mud of some basins; this organogenic mud is named *sapropel*. This is the ideal environmental condition to start the petroleum formation process.

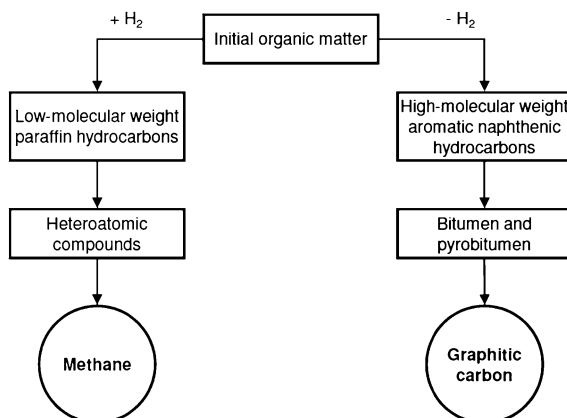
Figure 2.26 shows the typical scheme of these ideal environments: it is a lagoon basin, whose limited communication with the open sea leads to the stagnation of the water under the superficial layer with a low concentration of oxygen; hydrogen sulphide (H₂S) is developed as a consequence of the limited exchange of aerated water in the water. In this situation, the remains of microorganisms abundantly present in the aerated superficial layer accumulate at the bottom of water.

In normal conditions that is, to say in the presence of oxygen dissolved in water, organic remains undergo the attack by aerobic bacteria,²⁶ that while oxidizing the organic carbon, bring these remains back to the marine cycle, under the form of various chemical compounds. This does not take place when such organic materials are in an oxygen-free environment, where the action of anaerobic bacteria

²⁵ During the XIX century, many supported the *inorganic origin of petroleum*. In fact, it is theoretically possible that the formation of hydrocarbons through chemical processes that occur among inorganic compounds of petroleum, or by polymerisation of primordial methane making up the stellar matter; the presence of methane among volcanic gases is ascertained. It is however incompatible with the mechanisms characterising inorganic chemistry the formation of complex organic substances as those that can be found in petroleum, and is in any case difficult to justify the distribution of deposits, more abundant in the recent layers of the Earth's crust.

²⁶ *Aerobic bacteria* need free oxygen to develop their action; conversely, *anaerobic bacteria* only use combined oxygen.

Fig. 2.27 Simplified diagram of naftogenesis [10]



prevails, and they use the oxygen belonging to organic molecules and, through fermentation processes, mainly produce carbon dioxide and methane.

In environments similar to the one described above, through given biochemical reactions and the influence of some physical factors as temperature and pressure, the so-called *naftogenesis* occurs, which transforms organic raw materials into the compounds that make up petroleum (Fig. 2.27).

Furthermore, in order to allow environmental conditions to remain unchanged, it is necessary that depths undergo a continuous and regular lowering called *subsidence*, able to offset the supply of sediments; in this way, large quantities of organic matter will settle for very long times (several geological eras), without assisting to an interruption of the conditions favourable to deposit.

The slow and progressive subsidence of the Earth's crust, determined by both the attraction action of underlying fluid levels, and by the weight of sediments themselves, allows an accumulation of organic matter included in detritus, which reach several kilometres in thickness, although generally the waters above have limited depths (ranging from a few meters to a few hundreds of meters).

The subsidence of sedimentary sequences is also important since the reaching of higher and higher depths leads to an increase in their temperature, in consideration of the *geothermal gradient*, originated from the endogenous heat of the earth. The action of temperature and its persistence for very long times, represent—as described afterwards—the pre-requirements for most of the chemical transformations of the organic matter.

Naftogenesis is a complex process, still not entirely known, from whose interpretation many theories were developed. One of the most exhaustive and accredited theories was presented by Tissot and Welte [9]. According to this theory, the naftogenesis process is divided into four stages:

- Diagenesis
- Catagenesis
- Metagenesis
- Metamorphism

Fig. 2.28 Possible evolution of organic matter in petroleum formation according to Tissot and Welte [9]

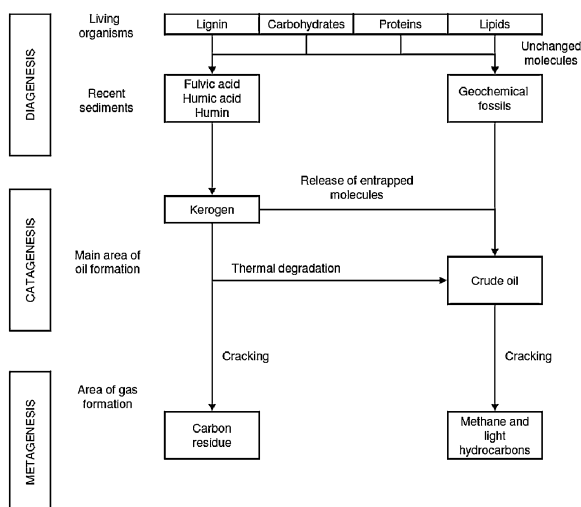


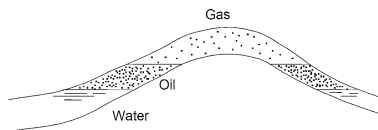
Figure 2.28 shows a simplified evolution of sediments in the first three phases of naftogenesis that is, to say those that properly concern petroleum formation.

Diagenesis begins as organic sediments and detritus settle on the bottom of the basin. During this first phase, deposits gradually reach depths of nearly 1,000 m and temperatures of about 50°C. Water, still present in relevant percentages, is partly expelled following *compaction*, a process due to the load exercised by the layers above and that, together with the *cementation* made by the salts dissolved in water, transforms inorganic detritus into sedimentary rock. Furthermore, an intense activity of aerobic and anaerobic bacteria takes place, whose quantity is not sufficient for the decomposition (and thence the disruption) of the organic matter. They operate the separation of *biopolymers*, that is to say the molecules that make up the organic matter, originating new structures made up of smaller and simpler organic molecules. Besides providing nutrition to bacteria, they tend to react among themselves, combining into new large molecular formations called *geopolymers*. In these compounds, the macromolecule with the highest concentration is *kerogen*.²⁷ This is the substance from which, thanks to the transformations occurring in the subsequent phases, petroleum originates.

Besides kerogen, representing the main derivative of the organic compound, high-molecular weight compounds are formed, defined as *geochemical fossils*, which are synthesised from plants and animals and absorbed in sediments. From a chronological standpoint, they represent the original substance from whose evolution hydrocarbons originate; consequently, they are considered as contributing—

²⁷ *Kerogen* is an organic matter composed of carbon, hydrogen and oxygen; three main types of kerogen exist, with different evolution and therefore leading to different end product; they are differentiated according to the relative quantities of hydrogen and oxygen compared to carbon.

Fig. 2.29 Schematic diagram of a typical oil field [11]



although marginally—to petroleum formation, since the origin of the latter is mainly ascribed to the transformation that kerogen undergoes with depths.

Sometimes the sediment that settles in basins is particularly rich in vegetable substances, derived from terrestrial plants; this mainly happens in lake basins surrounded by abundant vegetation and in coastal marshes of tropical areas, where a typical thick vegetation grows. In this way, layers of sediments mainly made up of vegetable materials are formed and, at the end of diagenesis, essentially originate peats, lignite and brown coals, in which the structure of the plants of origin is still clearly recognisable.

Catagenesis intervenes when, due to subsidence, the thickness of sediments exceeds 2,000 m, and high values of pressure (from 300 up to 1,000–1,500 bars) and temperature (nearly 150°C) are generated. As an effect of pressure, sedimentary rock porosity and permeability decrease, a further quantity of water is expelled, and salinity increases in the remaining portion. In this stage, the major changes in kerogen take place, and lead to the degradation of its molecules.

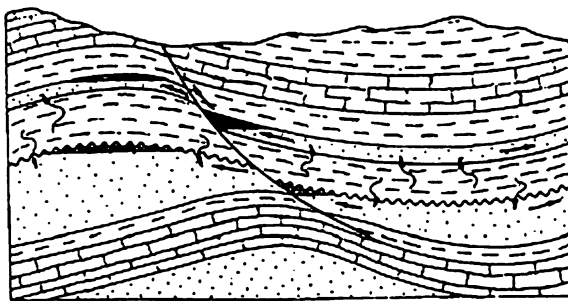
In this phase, the factors that influence the development of kerogen and the formation of petroleum mainly include *temperature* and *duration*, which characterise the heating and transformation processes of kerogen. These factors are linked proportionally—in the sense that the same result can be achieved at high temperature in short times and, vice versa, in long times at lower temperature. In this phase, methane develops as well, whereas the petroleum produced in the *parent rock* that is to say the rock in which the initial organic compound was contained, once a given quantity is exceeded, is ejected and penetrates the surrounding rocks. This is therefore the beginning of migration that brings crude oil to the so-called *reservoir rocks*, in which real oilfields are localised.

Metagenesis represents the last stage of evolution of the organic compound, and takes place at high depths reaching 5–6 km, and at temperatures of 150–200°C. Kerogen molecules lose almost all the oxygen atoms and most of hydrogen atoms, producing limited quantities of methane, whereas—at the end of this phase—they originate a carbon residue, destined to become *graphite*.

Temperature increase also modifies the composition of part of the oil formed during the previous phase of catagenesis; in fact, a *thermal cracking* that is, to say the breaking of those oil molecules with a high-molecular weight, and the formation of smaller and lighter molecules that are destined to make up *light oil* and *gas* (mainly *methane*).

As a consequence of the high temperatures involved, several mineral sediments undergo solution and recrystallisation processes. Furthermore, they exercise a catalytic action in chemical reactions that, as far as hydrocarbons are concerned, lead to the formation of methane alone.

Fig. 2.30 Migration of petroleum from the parent rocks [12]



Metamorphism, finally, determines the total loss of the original features of organic sediments. Hydrocarbons are not involved in this stage, whereas what remains of the original constituents of kerogen is transformed into graphite.

As already mentioned, *temperature* is the guiding factor of naftogenesis, since some of the chemical-physical reactions that transform organic compounds into petroleum only occur at temperatures close to 250–300°C. *Pressure*, on the contrary—which increases with the depth of sedimentary layers—mainly intervenes in determining the removal of fluids from the parent rock and their migration. In the final analysis, a typical petroleum formation is made up of a set of rocks impregnated of liquid and gaseous hydrocarbons, mixed with salty water (Fig. 2.29).

These formations are generally divided into *primary* and *secondary*, respectively, when petroleum is kept in the rocks of origin (*parent rocks*) or when because of the effect of compaction, it migrates to other rocks called *reservoir rocks*, different from those in which it was formed. In Fig. 2.30, which summarises the migration movement of petroleum that abandons parent rocks, arrows represent the direction of petroleum migration from parent rocks to the adjacent permeable rocks, allowing it to reach the reservoir rocks that represent the areas of accumulation (oilfields), and, in some cases, up to the surface. Parent rocks can have different natures: argillaceous, calcareous, siliceous, and carbonaceous. Impregnated rocks are generally sedimentary, sandstones or sands.

The geological eras which the formation of petroleum dates back to include, in order of importance: Cenozoic, Paleozoic and Mesozoic²⁸; only a few formations date back to more recent times, and more precisely to the Pleistocene period.

²⁸ This is the historical sequence of these eras:
 Palaeozoic era (from 570 to 225 million years ago);
 Mesozoic Era (from 225 to 65 million years ago);
 Cenozoic Era (from 65 to 2 million years ago).

Table 2.6 Conversion values of API degrees

API degrees	Relative density
0	1.076
10	1.000
15	0.966
20	0.934
25	0.904
30	0.876
35	0.850
40	0.825
45	0.802
50	0.780

2.4.2.3 Physical Properties and Technological Merits of Petroleum

In nature, it is not possible to find two oilfields providing petroleum with the same composition. They are different to such an extent that sometimes there are changes in the petroleum of the same oil well at the moment of extraction. It is therefore necessary to carefully assess the characteristics of each crude oil, in order to identify the appropriate refining processes.

From the energy viewpoint, the main property is the *lower calorific value*. In case of petroleum, different from what one might expect because of the variability of its composition, the lower heating value has a little variable value (9,600–10,800 kcal/kg)²⁹; the *higher heating value* is generally higher by nearly 10%. The high energy density of petroleum is the main reason for the very large spread of this substance as a primary energy source.

Another important characteristic is *density* that is, to say the weight of the substance by unit of volume, which obviously varies according to temperature. From density it is possible to derive the first information on the refining processes to be followed; high-density crude oils, for instance, contain petrol in lower quantities and, consequently, are less valuable. Furthermore, as density increases, the calorific value decreases.

Usually, reference is made to *relative density*, that is to say the ratio between the oil mass under consideration and the mass of the same volume of water, both at a temperature of 60°F (15.6°C).³⁰

In density determination, API degrees are very much used, and they vary according to the relative density, based on the formula:

$$1^{\circ}\text{API} = \frac{141.5}{\text{relative density}} - 131.5$$

²⁹ Usually, a medium calorific value of 10,000 kcal/kg is considered, which is also the reference value for ton of oil equivalent. A t.o.e. has then a thermal content of 10^7 kcal, amounting to nearly 41.9×10^9 J = 41.9 GJ.

³⁰ Relative density differs from *specific gravity* since, although being a ratio between equal values of matter and water, it is calculated at a temperature of 4°C.

Table 2.7 General classification of hydrocarbons

	Structure	Series	Parent	Homologous
Saturated	Acyclic	Paraffin (C_nH_{2n+2})	Methane (CH_4)	Ethane Propane Butane Pentane
	Cyclic	Naphthenic (C_nH_{2n})	Cyclopropane (trimethylene) (C_3H_6)	Cyclobutane Cyclopentane
Unsaturated	Cyclic and polycyclic	Aromatic or Benzenic (C_nH_{2n-6})	Benzole (Benzene) (C_6H_6)	Toluene
	Acyclic	Olefinic Acetylenic (C_nH_{2n})	Ethylene (C_2H_4)	

Table 2.6 shows some values of API degrees with the corresponding relative density.

In general, petroleum has a relative density ranging from 0.950 to 0.750 kg/dm³ (17–57 API), with the most frequent values included between 0.950–0.850 (17–35 API).

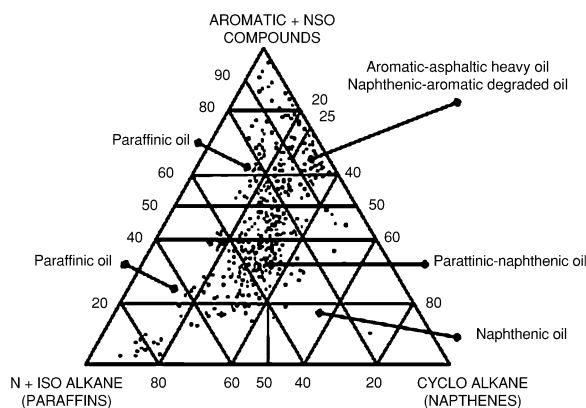
The other properties of petroleum include *viscosity*, whose determination is necessary for the extraction procedures.

For safety purposes, during transportation and storage, important items include the *flash point* (that is to say oil temperature at which the vapours released from it, in the presence of a flame, catch fire without creating combustion to petroleum itself) and the *burning point*, which corresponds to the temperature of oil at which vapours develop at such quantities that, if triggered, are also able to fire the liquid petroleum. As to the transportation of crude oil through the pipelines crossing cold regions, it is also important to take into account the *freezing point* (*pour point*), that is to say the temperature below which petroleum is completely coagulated and does not flow any longer. As regards petroleum containing paraffin solutions, instead of the pour point, the temperature at which paraffin starts to solidify (*cloud point*) is taken into consideration, producing a “cloud of wax”. Finally, the *boiling point* of the different components of crude oil, sets the reference temperatures for *fractional distillation*.

2.4.2.4 Composition and Classification of Petroleum

As already said, petroleum is made up of mixtures and solutions of many hydrocarbons (liquid, gaseous and solid), with relatively scarce quantities of other organic, oxygenated, sulphured and nitrogenous compounds. Because of this complex composition, there is no any systematic classification system. In any case, in the determination of the various types of crude oil, the hydrocarbons composing them are mainly taken into consideration.

Fig. 2.31 Ternary diagram of petroleum composition [9]



A basic criterion consists in the subdivision of hydrocarbons into *saturated* (carbon atoms saturated by simple bonds) and *unsaturated* (double or triple bonds between carbon atoms).

A second classification, based on the molecular structure, divides the hydrocarbons contained in crude oil into:

- *Acyclic* (or *aliphatic*) with carbon atoms bonded as an open chain;
- *Cyclic* with carbon atoms bonded as a closed chain;
- *Polycyclic* with the chain containing several links.

As regards these two classifications, the main hydrocarbons can be divided into three series characterised as follows:

- *Paraffin series*, saturated hydrocarbons, acyclic.
- *Naphthenic series*, saturated hydrocarbons, cyclic.
- *Aromatic series* (or *benzene*), cyclic and polycyclic unsaturated hydrocarbons.

There are then two other categories less important in the oil sector: *olefins* and *acetylene series*; both of them are characterised by acyclic unsaturated hydrocarbons.

Table 2.7 shows a schematic subdivision of hydrocarbons according to the criteria mentioned above.

Usually, petroleum contains at the same time the three main series mentioned above; Fig. 2.31 shows the ternary diagram of petroleum composition.

According to the prevailing series of hydrocarbons, petroleum can be divided into *paraffinic*, *naphthenic*, *aromatic* and *mixed*.

Paraffinic petroleum contains abundant dissolved quantities (up to 10%) of solid paraffin (called *petroleum wax*). Many oil fields with paraffinic petroleum are located in the USA (Pennsylvania, Ohio, Oklahoma and Texas) and in Europe (Galicia and Romania). The residues of distillation are characterised by a light colour.

Naphthenic petroleum contains high percentages of cyclopentane and dicycloesane (naphthenic series) and large quantities of asphalt (for this reason called

asphaltic petroleum), whereas it is poor in solid paraffin (maximum accounting for 1.5%). Naphthenic petroleum is the majority of oil available in Russia, and part of the petroleum available in Romania and America (California, Mexico and South America). After distillation, it shows a dark-coloured residue.

Aromatic petroleum contains hydrocarbons of the aromatic series for a maximum percentage of 40% and solid paraffin is present in quantities lower than 5%. In this case as well, the residue of distillation is dark-coloured. This petroleum is mainly available in the Middle East, Japan and in South-East Asia.

Mixed petroleum does not show a dominating series of hydrocarbons, although very often there is a predominance of paraffin and naphthene.

As regards the *minor substances* present in petroleum, they are mainly made up of *oxygen, sulphur and nitrogen*.

Oxygen can be found in petroleum both in a free state and as a component of several organic compounds; furthermore, due to air exposure, several oxygenated substances are formed. In general, oxygen content grows with the specific gravity of petroleum; in asphalts, for instance, it may also reach 5%.

Sulphur is present in all crude oils, both in a free state and as a component of H_2S , and of many sulphurated organic compounds. Usually, in crude oils with a low specific gravity there is a low sulphur content, in the same way as the lightest fractions of whatever type of petroleum are, in general, poor in sulphur. Crude oils with a sulphur content higher than 0.5% are called *sulphurous (high-sulphur crudes)*. In asphalts, finally, contents are very high, even exceeding 10%.

Nitrogen is contained in all types of petroleum, generally in quantities lower than 0.5%, with maximum peaks of 2%. Also in this case, it is available in the free state, or in organic compounds. Among nitrogenous substances, particular importance is ascribed to *porphyrines*, not for their features, but rather because they provide indirect confirmation of the theory on the organic origin of petroleum; these substances are, in fact, exclusively derived from haemoglobin and chlorophyll.

The microscopic study of petroleum also showed that it may contain different materials of organic origin, like, for instance, flakes of siliceous shells, fragments of insects, spores, algae and unicellular organisms (also living ones).

Finally, petroleum has an inorganic content that is shown in combustion-originated ash. Ashes, mainly made up of salts, generally represent 0.01–0.05% of crude oil weight, and their level increases as the weight density of oils increases; in asphaltic ones, it is possible to reach 1%.

2.4.2.5 Treatment and Use

The petroleum extracted from oil fields is generally subsequently refined (some Arab countries also use it directly), to obtain products with a higher energy content and a better combustion capability.

From crude oil it is possible to derive:

- Gas
- Gasoline
- Kerosene
- Diesel oil
- Lubricant bases
- Fuel oil
- Bitumen
- Other products.

2.4.2.6 Oil reserves and Geographical Distribution

The definition “oil reserves” generally indicates the quantity of petroleum that can be cost-effectively drilled from oil fields either through flowing wells or by means of suitable interventions (repressurisation, fluidization, pumping, etc.).

The recoverable quantity of the petroleum originally present in the oil field depends on many factors; in particular, it varies according to the hydrocarbons composing it and to the type of rock containing it. This percentage may range between 10 and 50% of the real quantity of oil originally present in the field, called *original oil in place* (OOIP).

The determination of the quantity of petroleum still present in a production basin or in a newly discovered oil field implies a careful geological and chemical analysis. It is however necessary to underline that very often the official assessment is heavily influenced by political and economic interests.

However, thanks to the improvement of surveying and production methodologies, the crude oil reserves which can be really exploited are destined to increase. Furthermore, despite the objective difficulties in the determination of the real capacity of an oil field, large areas of the Earth—first of all seabed—are still nowadays almost entirely unexplored, and this justifies a certain optimism.

Table 2.8 shows the data on the distribution of ascertained petroleum reserves. It shows that these reserves are almost exclusively concentrated in some geographical areas. In fact, over 60% of oil fields are located in the Middle East. In particular, Saudi Arabia—the richest country in petroleum—hosts over one-fifth of world reserves, followed by Iran, Iraq, Kuwait, United Arab Emirates, Venezuela (the first non-Middle East country), and the Russian Federation (Fig. 2.32).

Based on the present production and consumption rates, the estimated availability of petroleum apparently guarantees stocks for the next 42 years (Fig. 2.33).

Table 2.8 Ascertained oil reserves at the end of 2007 [8]

	10 ⁹ tonnes	10 ⁹ barrels	%
USA	3.6	29.4	2.4
Canada	4.2	27.7	2.2
Mexico	1.7	12.2	1.0
<i>Total North America</i>	9.5	69.3	5.6
Argentina	0.4	2.6	0.2
Brazil	1.7	12.6	1.0
Colombia	0.2	1.5	0.1
Ecuador	0.6	4.3	0.3
Peru	0.1	1.1	0.1
Trinidad and Tobago	0.1	0.8	0.1
Venezuela	12.5	87.0	7.0
Other Central America	0.2	1.3	0.1
<i>Total South and Central America</i>	15.8	111.2	9.0
Azerbaijan	1.0	7.0	0.6
Denmark	0.1	1.1	0.1
Italy	0.1	0.8	0.1
Kazakhstan	5.3	39.8	3.2
Norway	1.0	8.2	0.7
Romania	0.1	0.5	0.0
Russian Federation	10.9	79.4	6.4
Turkmenistan	0.1	0.6	0.0
Great Britain	0.5	3.6	0.3
Uzbekistan	0.1	0.6	0.0
Others	0.3	2.1	0.2
<i>Total Europe and Eurasia</i>	19.5	143.7	11.6
Iran	19.0	138.4	11.2
Iraq	15.5	115.0	9.3
Kuwait	14.0	101.5	8.2
Oman	0.8	5.6	0.5
Qatar	3.6	27.4	2.2
Saudi Arabia	36.3	264.2	21.3
Syria	0.3	2.5	0.2
United Arab Emirates	13.0	97.8	7.9
Yemen	0.4	2.8	0.2
Others	—	0.1	0.0
<i>Total Middle East</i>	102.9	755.3	61.0
Algeria	1.5	12.3	1.0
Angola	1.2	9.0	0.7
Chad	0.1	0.9	0.1
Republic of Congo	0.3	1.9	0.2
Egypt	0.5	4.1	0.3
Equatorial Guinea	0.2	1.8	0.1
Gabon	0.3	2.0	0.2
Libya	5.4	41.5	3.4
Nigeria	4.9	36.2	2.9

(continued)

Table 2.8 (continued)

	10 ⁹ tonnes	10 ⁹ barrels	%
Sudan	0.9	6.6	0.5
Tunisia	0.1	0.6	0.0
Others	0.1	0.6	0.0
<i>Total Africa</i>	15.5	117.5	9.5
Australia	0.4	4.2	0.3
Brunei	0.2	1.2	0.1
China	2.1	15.5	1.3
India	0.7	5.5	0.4
Indonesia	0.6	4.4	0.4
Malaysia	0.7	5.4	0.4
Thailand	0.1	0.5	0.0
Vietnam	0.5	3.4	0.3
Others	0.1	0.9	0.1
<i>Total Pacific Area</i>	5.4	41.0	3.3
<i>Total world</i>	168.6	1,238.0	100.0

Fig. 2.32 Distribution of world oil reserves [8]

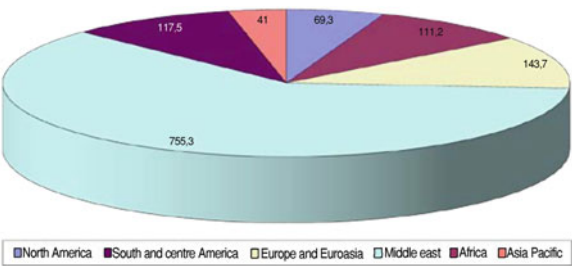
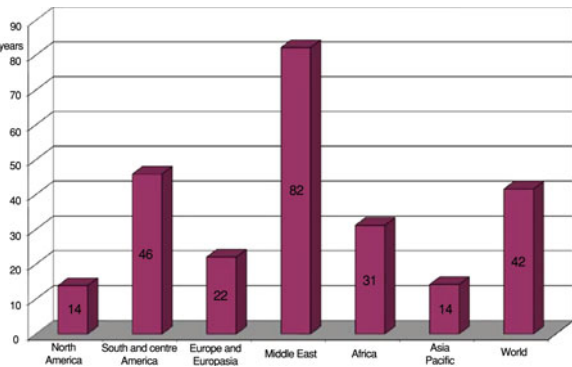


Fig. 2.33 Oil consumption/production ratio [8]



2.4.3 Tar Sands

Tar sands are sedimentary rocks (either coherent or incoherent) containing bitumen³¹ or another type of thick petroleum, which cannot be drilled with the conventional methods used for petroleum with an API³² density below 12°.

These sands, usually quartzous, originated from lake and river sediments, and deposited on the layer of parent rocks between the end of the Upper Devonian and the beginning of the Lower Cretaceous (in a time leg that lasted nearly 225 million years). Through this contact, they absorbed the underlying oil and gas, hence saturating over 90% of their porosity. In this way, an oily content was created, whose weight reaches a maximum of 18–20% of sand mass, and that therefore has a typically *wet* appearance.

In particular, tar sands are traced back to the Lower Cretaceous³³ and derive their tar content from the underlying layers of parent rocks dating back to Upper Devonian³⁴ and rich in organic remains.

Tar sand stocks amount to nearly 2/3 of our Planet's oil stocks; the main deposits are located in Canada (1,700 billion barrels, corresponding to $270 \times 10^9 \text{ m}^3$ in the deposit of Athabasca) and Venezuela (235 billion barrels, corresponding to $37 \times 10^9 \text{ m}^3$ in the deposit of Orinoco). Overall, the Canadian and Venezuelan deposits contain $570 \times 10^9 \text{ m}^3$ of petroleum, corresponding to $280 \times 10^9 \text{ m}^3$ of conventional petroleum, far more than the one contained in the subsoil of Saudi Arabia and of Middle East Countries. Tar sands reserves are also present in Russia and Middle East, although the largest deposits are the two ones mentioned above.

In consideration of their size, the deposits of this energy source arouse increasing interest, mainly in Canada, which depends upon a concrete technical and economic difficulty for the exploitation in percentages comparable to conventional fields. This is the reason for the previous reluctance in promoting research campaigns, especially by those Countries that have at one's disposal abundant quantities of petroleum.

³¹ Bitumen, together with other types of heavy oils available in these sands, belongs to solid or semisolid hydrocarbons. They are composed of high-molecular weight complex blends, whose chemical knowledge is imperfect because of analysis difficulties. This category also includes the asphalts used for road paving.

³² Cf. Sect. 2.4.2.3.

³³ Geological period belonging to the Mesozoic Era, dating back to nearly 135 million years ago.

³⁴ Geological period belonging to the Palaeozoic Era, dating back to nearly 360 million years ago.

Table 2.9 Typical composition of natural gas

Gas		Content (%)
Methane	CH ₄	70–90
Ethane	C ₂ H ₆	0–20
Propane	C ₃ H ₈	
Butane	C ₄ H ₁₀	
Carbon dioxide	CO ₂	0–8
Oxygen	O ₂	0–0.2
Nitrogen	N ₂	0–5
Hydrogen sulphide	H ₂ S	0–5
Rare gases	A, He, Ne, Xe	Traces

Source <http://www.naturalgas.org>

2.4.4 Natural Gas

2.4.4.1 General Description and Genesis

Mostly made up of gaseous hydrocarbons and by other gases in variable quantities, natural gas can be found both in its own deposits, and combined to petroleum. Therefore, the following different configurations can be identified, which often coexist;

- Gas is *free* and occupies the upper part of the deposit, whereas below there is petroleum or, in the absence of petroleum, it overhangs the areas of parent rock soaked with generally salty water;
- Gas is *dissolved in oil* and the quantity in solution varies according to pressure and temperature conditions in the deposit, and with the physical characteristics of oil and of the gas mixture;
- Gas is *dissolved in water*, whenever it is in the gas–water interface of free gas deposits, or completely dissolved in gas–waters deposits, as those in the Po Delta. In consideration of the high pressure and temperature levels detected in these deposits, the water solubility of natural gas reaches remarkable values, also amounting to some hundreds of percentage points in volume;
- Gas is *liquefied* when, at depths exceeding 2,000 m and in conditions of high pressure and temperature, natural gas and petroleum form a single liquid phase, physically indistinguishable (*condensate*).

There are then still undetermined quantities—or determined with a large approximation—of natural gas “entrapped” in complex crystalline structures, consisting a water molecules linked through hydrogen, methane and/or other gas bonds, including, in particular, gaseous hydrocarbons. In order to remain stable, these crystals must be in particular temperature and pressure conditions.

According to many researchers—also on the basis of studies carried out as from the '60s on this particular energy source made up of the so-called *gas hydrates* (or *methane hydrates* or *clathrates*)—this might represent one of the primary energy sources of the future. In fact, in free and in suitable conditions the gas entrapped in

the cavities of crystal lattice and originated from water molecules, it is possible to derive natural fuel gas.

The *genesis* of gaseous hydrocarbons representing the energy source called *natural gas* is strictly related to the modes and conditions of formation of liquid hydrocarbons (see Sect. 2.4.2.2), since both derive from a common matrix.

The chemical analysis of natural gas is by far less complex than petroleum, because of the lower number of its compounds and their simplicity; it is performed through distillation by means of mass spectrometers and gas chromatographs.

As to its composition, *methane* is the hydrocarbon present in the highest percentage; for this reason, people tend to use the word *methane* as a synonym of natural gas. The other compounds generally belong to the paraffin series and to olefins (ethylene in particular). If the deposit also contains petroleum, then the quantity of hydrocarbons other than methane (ethane, propane, butane and higher) may reach 50%.

Natural gases are classified into *dry*, *lean* and *wet*, according to the content in liquid hydrocarbon vapours. Vapour content represents a point of strength, since they can be separated,³⁵ condensed and used for the production of *light diesel oils*.

Another characteristic that enhances natural gas is the presence, more or less marked, of *propane* and *butane* in quantities that make its separation economically convenient. These hydrocarbons, whose liquefaction is simple and occurs at a relatively low pressure, are very much used as fuels and marketed in easily transportable cylinders, at a pressure of 4–6 bars, with a composition of 60–70% butane and 30–40% propane; their product name is *liquefied petroleum gas* (LPG).

The other main gases that can be identified in natural gas include nitrogen (N₂), carbon dioxide (CO₂), hydrogen sulphide (H₂S) and, rarely, hydrogen (H₂), carbon oxide (CO) and helium (He) (Table 2.9).

As regards the lower heating value, the average value of 12,000 kcal/kg can be considered, that is to say 8.200 kcal/m³.

Among the main values linked to natural gas, besides *density* (both *absolute* and *relative*) and specific gravity,³⁶ particular importance is also ascribed to *pressure*, *temperature*, *volume* and *flow rate*. The latter, very much used especially in transportation phases, is generally expressed in m³/h and, when referred to normal conditions, is measured in Nm³/h.

Over the last decades, natural gas gained a growing importance in energy markets.

Although the areas rich in crude oil are generally also rich in natural gas, not always the importance of the latter in the scale of production of primary sources has been considered as the former. Its main *drawbacks* include the *need for major financial investments* and *technological hindrances*, mostly linked to the transportation problems due to its gaseous physical state. The transportation of natural

³⁵ Through the so-called “*degasolination*” process.

³⁶ As regards absolute density and specific gravity in natural gas compared to liquid fuel, the dependency from pressure and temperature is higher. Methane relative density amounts to 0.57.

gas, in fact, demands large infrastructures, gas pipelines, sometimes long thousands of kilometres, with pumping and decompression plants and widespread distribution networks.

The political stability of producing Countries as well as of the Countries of transit of gas pipelines is key for supplies. Furthermore, natural gas demands particular caution during distribution, due to the risk of gas leaks and explosions. Finally, another of its drawbacks is the fact that combustion—that is triggered at a high flame temperature—entails a high development of nitric oxides. In the past, this aptitude determined some marketing difficulties.

Another drawback of natural gas is represented by the fact that *it is not possible to have a constant flow rate of gas for the entire life of the deposit*; the production profile, in fact, rapidly peaks during the first years of gas extraction, and then slowly decreases for the rest of the life of the deposit.³⁷

However, natural gas has many of the *advantages of petroleum* and, in addition, *further positive aspects* as, for instance, a limited global production of polluting substances and of CO₂ following its combustion. With respect to the already mentioned development of nitric oxides, methane combustion determines:

- A reduction of CO₂ emissions accounting for 50% compared to the CO₂ produced by coal and 30% compared to petroleum³⁸;
- Total or nearly total absence of sulphur oxides, particulate, metals and non-combustible residues.

Other advantages of natural gas include the higher efficiency of combustion and its high calorific value (12,000 kcal/kg).

Particularly noticeable is also the *availability* ensured by the diversification of stocks, possible thanks to a geopolitical distribution far less critical than petroleum.

The setting up of gas storage reservoirs, possibly in areas close to highly consuming regions, can be carried out through the utilisation of:

- Gas deposits close to depletion (during the period of low consumption, generally in summer, the gas coming from distant deposits or from import is pumped in the storage reservoir in order to be extracted during the peaks of demand).
- Reservoirs in the liquefied natural gas regasification plants, which allow a rapid conversion and availability of natural gas.
- The transportation routes of the network of gas pipelines, in which the operating pressure is higher than the distribution pressure, can also be considered as storage reservoirs to be used in the periods of daily peaks.

³⁷ Sometimes this behaviour can be seen—although more limitedly—also in crude oil fields.

³⁸ Given the same energy produced through combustion.

Table 2.10 Natural gas reserves ascertained at the end of 2007 [8]

	10^{12} m^3	%
USA	5.98	3.4
Canada	1.63	0.9
Mexico	0.37	0.2
<i>Total North America</i>	7.98	4.5
Argentina	0.44	0.2
Bolivia	0.74	0.4
Brazil	0.36	0.2
Peru	0.13	0.1
Colombia	0.36	0.2
Trinidad & Tobago	0.48	0.3
Venezuela	5.15	2.9
Others	0.07	0.0
<i>Total South and Central America</i>	7.73	4.4
Azerbaijan	1.28	0.7
Denmark	0.12	0.1
Germany	0.14	0.1
Italy	0.09	0.1
Kazakhstan	1.90	1.1
The Netherlands	1.25	0.7
Norway	2.96	1.7
Poland	0.11	0.1
Romania	0.63	0.4
Russian Federation	44.65	25.2
Turkmenistan	2.67	1.5
Ukraine	1.03	0.6
Great Britain	0.41	0.2
Uzbekistan	1.74	1.0
Others	0.43	0.2
<i>Total Europe and Eurasia</i>	59.41	33.5
Bahrain	0.09	0.1
Iran	27.80	15.7
Iraq	3.17	1.8
Kuwait	1.78	1.0
Oman	0.69	0.4
Qatar	25.60	14.4
Saudi Arabia	7.17	4.0
Syria	0.29	0.2
United Arab Emirates	6.09	3.4
Yemen	0.49	0.3
Others	0.05	0.0
<i>Total Middle East</i>	73.22	41.3
Algeria	4.51	2.5
Egypt	2.06	1.2
Libya	1.50	0.8
Nigeria	5.30	3.0
Others	1.21	0.7

(continued)

Table 2.10 (continued)

	10^{12} m^3	%
Total Africa	14.58	8.2
Australia	2.51	1.4
Bangladesh	0.39	0.2
Brunei	0.34	0.2
China	1.88	1.1
India	1.06	0.6
Indonesia	3.00	1.7
Malaysia	2.47	1.4
Myanmar	0.60	0.3
Pakistan	0.85	0.5
Papua New Guinea	0.44	0.2
Thailand	0.33	0.2
Vietnam	0.22	0.1
Others	0.37	0.2
Total Pacific Area	14.46	8.2
Total world	177.38	100.0

Fig. 2.34 Distribution of natural gas reserves all over the world

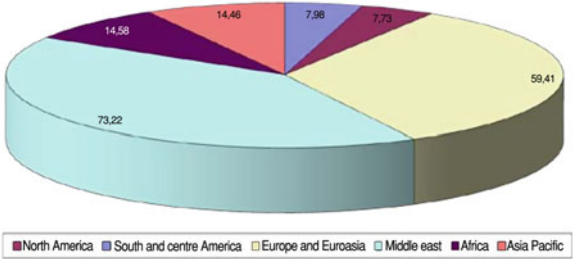


Fig. 2.35 Natural gas production/consumption ratio

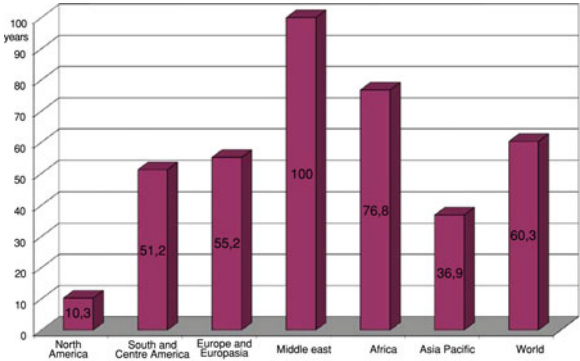
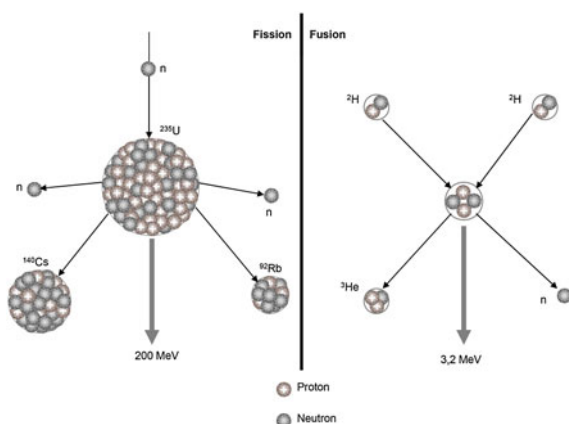


Fig. 2.36 Nuclear fission and fusion



2.4.4.2 Processing and Utilisation

Very often, methane is used in the form in which it is extracted, without any processing whatsoever; its gaseous state allows its good distribution in the short range (long-range distribution is costly, while transoceanic distribution is highly difficult).

2.4.4.3 Geographical Distribution and Reserves

Table 2.10 shows the distribution of natural gas reserves ascertained in the different geographical areas (Fig. 2.34).

On the basis of present production rate, stock would cover nearly 60 years (Fig. 2.35).

Because of the technological problems that make its transportation more expensive, the growth in natural gas consumption mainly occurred in industrialised countries, whereas there are still large intact deposits in regions located far away from the areas of consumption, mainly in some newly industrialising countries.

Due to the difficulties mentioned above, in fact, many Countries potentially rich in natural gas do not extract it or decide to extract limited quantities of it. So, for instance, the present phase of intensive exploitation of petroleum allows the Arab Countries in the Middle East to preserve the huge gas reserves located in their areas to use them when oil begins to be in short supply.

As far as the huge reserves of the ex-USSR are concerned, shorter times of depletion are envisaged, since they are destined, already nowadays, to cover a larger portion of European consumption.

2.4.5 Nuclear Power

Nuclear power is released, in huge quantities, by reactions that determine transmutations of given elements. The quantity of energy derived from these

reactions can be calculated through the well-known Einstein relation that links mass and energy.³⁹ The calculation is based on the *mass defect* that the products of the reaction show compared to the elements involved in the reaction itself.

The remarkable difference between the quantities of energy that develop through these reactions and those linked to combustion is explained with the fact that in the latter the forces keeping electrons are exploited, hence involving the outer levels of the atom, whereas in nuclear reactions the nucleus of atom is *decomposed or in any case it undergoes a transformation*, and during these actions higher forces come into play. For instance, the energy generated through fission by 1 g of uranium is equivalent to nearly 8.4×10^{10} J, whereas the one released through combustion by 1 g of gasoline is equal to nearly 4.84×10^4 J; given the same masses, then the ratio between the two energy capacities amounts to nearly 24×10^6 .

The chemical elements involving spontaneous nuclear reactions are called *radioisotopes* and can be either *natural* or *artificial*.

The processes that make this form of energy available include the *fission* of nuclei with a high atomic weight and the *fusion*⁴⁰ of light nuclei.

2.4.5.1 Energy Use of Nuclear Power

Nuclear power can be exploited in two ways:

1. Through the *fission* of the *uranium* atom
2. Through the *fusion* of two *hydrogen* atoms.

If, on the one hand, the fission technology has been available for a few decades, fusion, on the other hand, is still undergoing a pre-commercial development phase.

The uranium used for fission purposes is contained in its minerals in quantities ranging between 0.1 and 0.5%, and is 0.71% made up of isotope ^{235}U , 99.28% of isotope ^{238}U and the remaining 0.01% by isotope ^{234}U ; the “fissile” one that is, to say useful for nuclear fission, is ^{235}U , present in a much lower percentage. For this reason, uranium generally undergoes “enrichment” to obtain higher percentages of the fissile isotope.

³⁹ This is the famous equation $E = mc^2$, where e is, by definition, the value of nuclear power owned by a mass, m is the so-called *mass defect* and c is the speed of light ($c \cong 3 \times 10^8$ m/s). The mass value of a nucleus, theoretically calculated by adding up the masses of neutrons and protons that compose it, is higher than the one experimentally calculated, and the difference between the two quantities is precisely the mass defect.

⁴⁰ This is a reaction in which, through the fusion of nuclei of light elements, a mass nucleus lower than the sum of the initial masses is formed, and energy is generated in a quantity proportional to this mass defect.

From fission, through one neuron, of a ^{235}U atom (Fig. 2.36) it is possible to obtain one cesium atom, one of rubidium, two neurons⁴¹ and a quantity of energy amounting to 200 MeV.⁴²

From the fusion of two hydrogen atoms, it is possible to obtain one helium atom and a quantity of energy amounting to 3.2 MeV.

In consideration of molecular weights and by comparing the energy released given the same mass, it is possible to derive that from the fission of 1 kg of ^{235}U 18.6 GWh are obtained, whereas from the fusion of 1 kg of hydrogen, 5,262 GWh are obtained.

Nuclear fission

In theory, all the elements with a sufficiently high atomic weight can undergo the fission process, that is to say the splitting of the nucleus through a neutron bombardment with a suitable energy level; in practice, however, only a few elements are *fissile* that is, to say able to really generate this reaction.

In nature, the only fissile element known is *uranium* (U), which is, therefore, the only primary source presently available for the fission process. *Natural uranium* is made up of a *mixture of three isotopes*, with an atomic weight of 234, 235 and 238, present in the percentages of 0.01, 0.71 and 99.28%, respectively. Isotope ^{235}U is the only fissile out of the three of them; the other fissile isotope of uranium, ^{233}U , is artificial and can be derived, through neutron bombardment, from isotope 232 of thorium (^{232}Th), that for this reason, is called *fertile* isotope, and can be numbered among the primary sources of nuclear power. Also uranium isotope 238 is fertile since, when undergoing suitable processing, originates plutonium 239 isotope (^{239}Pu), fissile as well. The next Chapter provides a description of the methods used to artificially increase the percentage of fissile isotopes.

Minerals containing uranium⁴³ and thorium are rather widespread throughout the surface of the Earth, but the concentrations of these minerals hardly make deposits economically interesting.

In any case uranium, out of these two elements, arouses the main interest. In the main deposits, minerals have an average uranium content of 1%; they are located in Australia, Nigeria, Brazil, Canada and United States.

⁴¹ Neutron emissions allow the fission reaction to be self-sustained (chain reaction); in fact, the neurons produced will affect other uranium atoms by causing other fissions that in turn produce other neurons, etc.

⁴² MeV: MegaelectronVolt. $1 \text{ MeV} = 1,60217646 \times 10^{-13} \text{ J}$.

⁴³ Those with the highest uranium content are *pitchblende* and *uranites*, made up of blends of uranium oxides in variable percentage. They are also called “primary minerals”, as opposed to “secondary minerals”, with a minor uranium content.

Nuclear Fusion

As far as *nuclear fusion* is concerned, there are no fine-tuned technological processes allowing the peaceful use of the energy produced by the relevant reactions, and consisting in the development of energy following the fusion of atoms or molecules of light elements. The main aim, in particular, is to reproduce in a much lower scale the nuclear reactions occurring in the sun. The most interesting chemical species for these reactions include some low-atomic weight elements, such as *deuterium* (D), *tritium* (T) and *lithium* (Li).

Deuterium and *tritium* are two hydrogen isotopes. They are present in nature in very low percentages compared to hydrogen.⁴⁴ The large spread of the latter element on earth makes in any case deuterium relatively abundant; in considering that only 1% of this isotope is concretely available, then the total world resources are considered as amounting to nearly 50×10^9 t.

Lithium is available in nature mainly in the form of oxide (Li_2O), but it can also be extracted from sea water when its concentration reaches 0.1 ppm, or it can be derived from those rocks where a quantity amounting to 20 ppm is present. The most suitable isotope for nuclear fusion is ^6Li , whose world availability amounts to nearly 67×10^4 t.

Finally, it is suitable to recall *natural radioisotopes*. They are grouped into four families and are characterised—besides by the number of neutrons present in the nucleus—also by their *half-life*.⁴⁵ Each of the four series starts from a *parent* that, with subsequent decays, generates the other radioactive isotopes of the family, until reaching a stable element (lead or bismuth) that closes the series.

2.4.5.2 Reserves and Geographical Distribution⁴⁶

Recent figures are those collected by the Nuclear Energy Agency (NEA) and are referred to 2003 estimates. The quantity of Uranium available in deposits, which can be extracted at the presently competitive cost of 80 \$/kg, amounts to around 2.5 Mt. Conversely, if a highest extraction price amounting to 130 \$/kg is considered as acceptable, then the reserves of Uranium increase to the value of 3.2 Mt.⁴⁷ Thus, at the today rate of consumption:

Enriched U derived from the one at 80 \$/kg R/P = 36 years.

Enriched U derived from the one at 130 \$/kg R/P = 47 years.

⁴⁴ The deuterium–hydrogen report is nearly 1–6,500; the percentage of tritium is, on the contrary, negligible (nearly $10^{-15}\%$).

⁴⁵ Is the time needed so that 50% of the atoms considered turn into stable elements through the natural decay process.

⁴⁶ Source <http://www.aspoitalia.it/documenti/coiante/nucleareidrogeno.html>

⁴⁷ Every 6 tons of natural U generate 1 ton of enriched U.

It is then necessary to stress that the strategic importance of nuclear power does not consist in the possibility of “controlling” uranium basins (that are also rather uniformly distributed from the geopolitical viewpoint), but rather in owning the updated “know-how” on the most economically-effective and efficient processes for the energy exploitation of the primary source.

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