Towards Sustainable Energy

Towards Sustainable Energy:

Mankind at the Crossroads

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Even from good things bad things happen to man, through his ignorance of how to use them or his desire to misuse them.

—Democritus of Abdera (460 b.C. – 370(?) b.C.)

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FOREWORD

Many years ago, following a series of unpredictable events, I entered the Electrochemistry Lab of the Universidad de Los Andes in Mérida, Venezuela. Pedro Aragón, the lab boss, asked me to make a literature review on the hydrogen evolution reaction and therefrom launch a research line. That was the beginning of my relationship with hydrogen and, since then, I have been involved with theoretical and experimental research on hydrogen production, employing different solvents and electrode materials and have also carried out feasibility studies on the use of hydrogen fuel cells for different market niches, as well as prospective analysis on the potential role of hydrogen in the energy transition which, in the last quarter of the XX century, was assumed as imminent because of the depletion of oil reserves.

We know now that oil reserves are far larger than what was then estimated, and fossil fuels consumption has increased continuously. As a consequence, the concentration of greenhouse gases has reached values that seriously endanger the Earth climate stability; then, reduction of those emissions is now an urgent goal, as pointed out by the Intergovernmental Panel on Climate Change convened by the United Nations organization.

The introduction of renewable energy sources, that are emission – free, is of course a significant contribution in attaining this goal, and important research and development efforts are devoted to the search of technological conditions that allow the substitution of fossil fuels as primary energy source. In fact, solar and wind high – power plants are presently operating.

On these grounds, public opinion receives encouraging messages from different agents in the energy sector. In the first one, the potential of wind and solar sources is emphasized, and hydrogen and advanced batteries as ancillary systems for energy storage and distribution, that should attend demands that cannot be satisfied by direct connection to the grid, are hailed as the final solution for transportation. A second, tacit, message implies that, with this scheme, cheap and abundant energy will continue to be available.

However, world energy demand has reached enormous values and its foreseeable growth in the next decades poses a gigantic hindrance. My purpose, in writing this book, is to provide interested readers with arguments that allow them to perceive the fundamental contradiction in both messages and comprehend that future energy provision is a serious challenge that has led mankind to a crossroads in which, in order to advance, difficult decisions must be made.

Preliminary Considerations

When energy topics are discussed, it is a recurrent fact that doubts arise due to a frequent confusion regarding the terms *energy* and *power* that, although intimately linked, refer to different physical quantities.

Energy can be defined as the ability to do physical work: displace an object, raise the temperature of a mass, sustain electricity flow through a body, etc.

By its side, power is defined as the amount of energy that a system is able to deliver in a certain time.

The energy unit in the International Units System is the Joule (J) which is the amount of work performed by a force of one Newton acting along a distance of one meter.

The unit for power in the same system is the Watt (W), which corresponds to a system that delivers one Joule in one second.

According to the type, and the scale, of the involved phenomena, it is useful to employ different units for these magnitudes.

In the case of energy, besides the Joule, the following units are employed:

- The Watt-hour (Wh) which is the energy delivered during one hour by a system with a power of one Watt.
- The calorie (cal) which is the energy needed to raise the temperature of one gram of water by one degree Celsius.
- The electron-volt (eV) which is the work done on an electron when it is accelerated by ã potential difference of one volt.

Conversion factors for these units are shown in the following table.

	1 J	1 Wh	1 cal	1 eV
1 J	1	2,778 x 10^{-4}	0,239	6,242 x 10^{18}
1 Wh	3.600	1	860,4	2,247 x 10^{22}
1 cal	4,184	1,162 x 10^{-3}	1	2,611 x 10^{19}
1 eV	1,602 x 10^{-19}	4,451 x 10^{-23}	3,829 x 10^{-20}	1

Moreover, multiples of these units, identified by a letter preceding the basic unit, are employed. For the case of the Joule, we have:

1 Kilojoule = 1 kJ = 1.000 J 1 Megajoule = 1 MJ = 1.000.000 J 1 Gigajoule = 1 GJ = 1.000.000.000 J
1 Terajoule = 1 TJ = 1.000.000.000.000 J = 10^{12} J 1 Petajoule = 1 PJ = 1.000.000.000.000.000 J = 10^{15} J
1 Exajoule = 1 EJ = 1.000.000.000.000.000.000 J = 10^{18} J

For the Wh case we have kWh, MWh, GWh, TWh, PWh, EWh

Analogously, for the case of power we have kW, MW, GW, TW, PW, EW

Furthermore, when considering fossil fuels, frequently employed units are the ton of coal, the barrel of oil and the gas cubic meter with the following equivalent values:

1 ton of coal equivalent = 29,3 GJ
1 oil barrel = 5,86 GJ
1 gas cubic meter = 37,3 MJ

CHAPTER 1

MAN AND ENERGY

1.1 Earth's energy balance

Thermodynamically, Earth can be considered as an open system that exchanges mass and energy with the Universe. Mass exchanges occur, sporadically, when bodies of different types enter the Earth´s gravitational field or when strong volcanic eruptions happen and particulate material is emitted from the Earth's gravitational field. However, when the size of the planet mass is considered, these exchanges can be taken as dismissible.

The case of energy is very different: exchange is continuous and depends, almost exclusively, on the amount of solar radiation that reaches the atmosphere with a mean power value of 340 W per square meter (Linsay, 2009; NOAA, 2023). Since the surface of Earth is 510 million of km^2, total radiation power amounts to 173 PW. This huge energy influx, which determines climate characteristics and makes possible life on Earth, is balanced by an emitted flux which impedes an energy accumulation that would have made life unsustainable. Thus, from the energy point of view, Earth can be approximately considered to be in a steady state in which the net energy flux is almost nil.

In order to understand the main aspects of this energy balance, it must be first pointed out that the energy emitted by the Sun is mostly high frequency (ultraviolet) electromagnetic radiation, and that quantitative analysis shows that 30% of the incoming energy flux is reflected, mainly by clouds, while 70% is absorbed, 23% by the atmosphere and 47% by the Earth surface. The high frequency radiation absorbed rises the temperature of both, atmosphere and surface, which, therefore, emit energy under the form of low frequency (infrared) radiation, thus maintaining the steady state.

It must be observed that if the compounds at the atmosphere were simple molecules, such as oxygen or nitrogen, that do not interact with infrared radiation, according to the Stefan – Boltzmann law the steady state would be attained at a temperature of 254 ^oK (-19^{o}C); however, other molecules are found in the atmosphere, such as water, carbon dioxide, methane, which do absorb infrared radiation, through the excitation of their vibrational frequencies, thus creating the so-called “natural greenhouse effect", responsible for having kept the average Earth temperature, during the last 6,000 years, at 15 ± 1^{o}C.

This is better understood if energy balances in three zones: at the upper limit of the atmosphere, within the atmosphere and on Earth’s surface, are separately analysed. In Tables 1.1.1, 1.1.2 and 1.1.3 partial balances for each zone are given in detail, and in Figure 1.1.1 (Goody and Yung, 1989) the corresponding energy fluxes are schematically shown.

ENERGY BALANCE AT THE ATMOSPHERE UPPER LIMIT			
ENERGY INPUT		ENERGY OUTPUT	
Units	Source	Units	Source
100	High frequency solar radiation	23	High frequency radiation reflected by clouds
		7	High frequency radiation reflected by the surface
		49	Infrared radiation emitted by the atmosphere
		9	Infrared radiation emitted by clouds
		12	Infrared radiation emitted by the surface
		100	Total emitted

Table 1.1.1. - Global energy balance

ENERGY BALANCE WITHIN THE ATMOSPHERE			
ENERGY INPUT		ENERGY OUTPUT	
Units	Source	Units	Source
19	High frequency solar radiation absorbed by the atmosphere	9	Infrared radiation emitted by clouds
4	High frequency solar radiation absorbed by clouds	49	Infrared radiation emitted by gases in the atmosphere
104	Infrared radiation emitted by the surface and absorbed by the atmosphere	98	Infrared radiation emitted by the atmosphere and absorbed by the surface
5	Convection of gases from the surface at higher temperature		
24	Vapour condensation		
156	Total absorbed	156	Total emitted

Table 1.1.2. - Energy balance within the atmosphere

ENERGY BALANCE AT EARTH'S SURFACE			
ENERGY INPUT		ENERGY OUTPUT	
Units	Source	Units	Source
47	Absorption of high frequency solar radiation	116	Infrared radiation emitted by the surface
98	Absorption of infrared radiation emitted by the atmosphere	5	Heat loss due to hot air convection
		24	Absorbed heat through evaporation and sublimation
145	Total absorbed	145	Total emitted

Table 1.1.3. - Energy balance at the surface

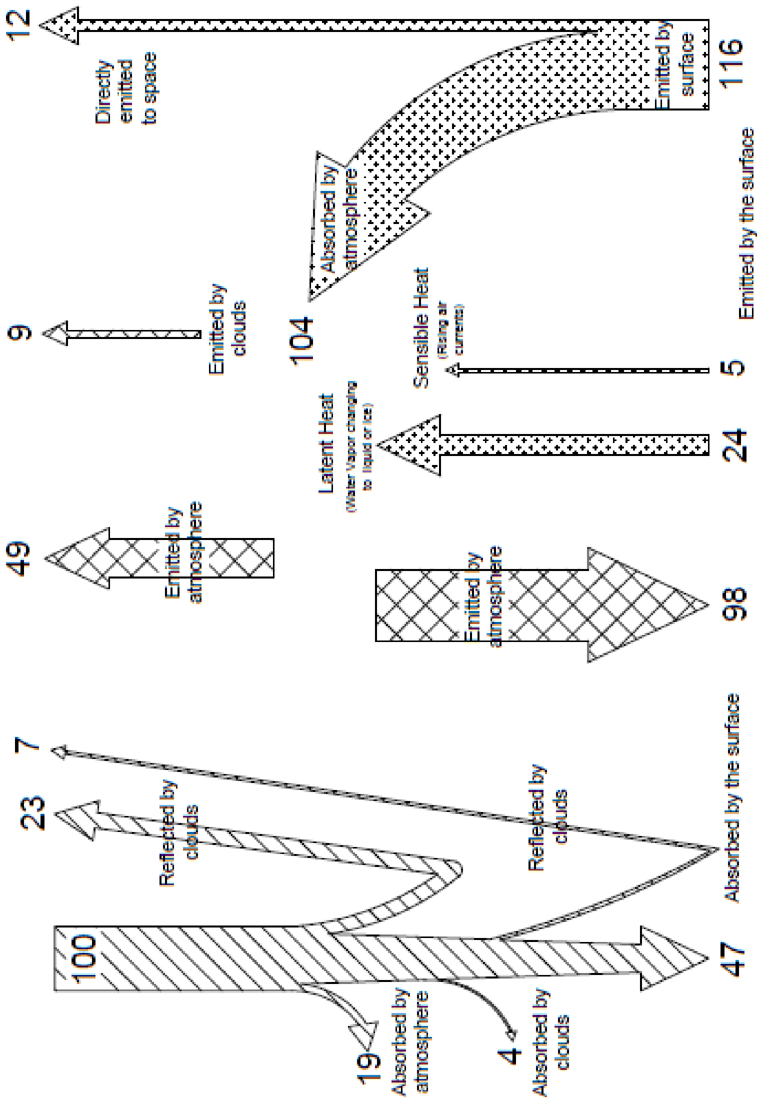

Figure 1.1.1.- Energy fluxes in the atmosphere.

However, for more than a century, the atmospheric concentration of molecules that absorb energy at infrared frequencies has been continuously increasing and, for such a reason, the Earth has left the stationary state and the present balance indicates a yearly energy gain of some tenths of Watt per square meter, which is mostly absorbed by the Southern Hemisphere oceans (Stephens and L´Ecuyer, 2015). This energy gain, which is about one thousandth of the total received energy, is the driving force of the climate change in which we are presently involved.

1.2 World energy consumption evolution

When studying the evolution of human beings, researchers have found fossils and tools from whose characteristics it was concluded that the advent of our lineage, *homo sapiens*, can be estimated to have happened *circa* 300,000 years ago (Handwerk, 2021). During the first stage, which goes up to about 10,000 b.C., the primitive man, mainly a hunter, learned to control the fire and, as a consequence, thermal energy was available with which, besides prey cooking, heating and lighting were made possible. *Per capita* energetic needs at that time have been estimated in some 6 kWh per day (Cook, 1971). Later on, by the year 6,000 b.C., our ancestors began to develop agricultural activities, wherefrom a higher amount of muscular work was necessary, leading the daily energy requirement to a value of about 12 kWh *per capita*. Centuries later, and in historic times, increasingly complex activities (metal working, fabrics making, mining, transportation) were started and energy consumption grew, reaching about 25 kWh *per capita* in the Middle Ages.

Energy consumption growth led to the improvement of life conditions and, consequently, life span was extended, and fertility rate underwent a significant increment, with the result that human population grew from about four million in 10,000 b.C. to some 400 million by 1400 (Roser, 2021).

Later on, the quality of life, and therefore the population growth, were enhanced by two major events, both initiated in England, that had deeply affected the structure and the evolution of human society: the "second agricultural revolution" and the "industrial revolution".

The second agricultural revolution was the consequence of the interaction between several technological, organizational, and economic innovations introduced since the XVI century that included (Sturgess, 1966):

- Crop rotation and introduction of new crops.
- Mixed use of land
- Better design and materials for ploughs
- Selective breeding
- Removal of common rights and inception of exclusive ownership of land
- Better transportation infrastructure
- Enlargement of agricultural area through land drainage and reclamation of natural prairies and forests
- Larger farms size
- Elimination of tariffs, tolls, and customs barriers

As a consequence of these changes, an 80% productivity growth was achieved in the 1500 – 1650 period (de Vries and van der Woude, 1997) with an associated, almost four-fold, increase of *per capita* energy consumption. More products at lower prices became available and population growth rate obviously accrued, with the effect that many persons moved from rural areas to cities and towns, where they found work in different forms of artisanal industries and in the services sector.

These effects were reinforced by the Industrial Revolution, whose start point may be established around 1760, when the first prototypes of steam machines were commercially available. Through the use of these devices it was possible to substitute muscular energy from men and beasts by mechanical work, obtained from the thermal energy released when wood or coal are burned. The introduction of different machines, able to perform various specific tasks, led to previously unimaginable productivity values in a large number of activities, as well as a diversification in the nature of the different produced goods. Steep increases in population and in energy consumption were the obvious consequences, as shown in Tables 1.2.1 and 1.2.2, built with data obtained from several authors (Cook, 1971; Roser. 2021; Martin-Amouroux, 2022; International Energy Agency, 2023).

It is clearly seen from these data that, since the beginning of the Industrial Revolution, energy consumption has been increasing at a much higher pace than population. In fact, in the 1850 – 2000 period a five – fold population increase took place, while energy consumption was expanded more than 20 times and, in the 1950 – 2020 period the energy consumption *per capita* was almost doubled, from 39 GJ (10.8 MWh) per year to 79 GJ (21.9 MWh).

YEAR	POPULATION Millions
1400	400
1450	420
1500	440
1550	470
1600	510
1650	550
1700	600
1750	790
1800	990
1850	1280
1900	1650
1950	2350
2000	6100
2020	7900

Table 1.2.1. - Earth population in the 1400 – 2020 period.

YEAR	ENERGY CONSUMPTION EJ
1400	0.04
1450	0.05
1500	0.08
1550	0.14
1600	0.20
1650	0.30
1700	0.59
1750	0.82
1800	2.31
1850	18.2
1900	45.9
1950	90.6
2000	388.0
2020	606.0

Table 1.2.2. - Primary energy consumption in the 1400 – 2020 period.

This relationship between productivity and energy consumption has evolved in a non-homogeneous way at different countries and, in fact, very important differences still exist, as shown in Table 1.2.3, where 2010 values of *per capita* GDP and *per capita* energy consumption are shown for several nations and in Figure 1.2.1 which clearly shows that a correlation exists between these two quantities.

COUNTRY	GDP *per capita*	Energy *per capita*	COUNTRY	GDP *per capita*	Energy *per capita*
	US$	MWh		US$	MWh
Niger	1115	0.41	Colombia	14649	11.15
Guinea	1831	0.68	Iran	15005	38.3
Uganda	2246	0.77	Thailand	17077	19.43
Tanzania	2582	0.91	China	17603	30.77
Cameroon	3700	1.59	Mexico	19086	17.52
Sudan	3701	2.32	Costa Rica	21199	11.96
Nigeria	4923	2.55	Argentina	21527	21.33
Ghana	5435	3.48	Uruguay	22801	18.32
Nicaragua	5639	4.26	Bulgaria	24398	32.22
Bangladesh	5911	2.83	Chili	25449	24.46
India	6592	6.81	Russia	27960	60.27
Filipinas	8095	4.79	Panama	29038	27.07
Guatemala	8927	5.71	Greece	29548	28.96
Iraq	8962	13.27	Turkey	31467	22.82
El Salvador	9086	7.08	Slovakia	31866	35.84
Tunisia	10398	9.52	Hungary	33593	29.25
Vietnam	10628	12.38	New Zealand	42915	45.91
Ecuador	10699	11.92	South Corea	44232	67.33
Argelia	11040	15.91	France	44993	40.46
Egypt	11566	9.64	Canada	47893	100.74
Perú	12515	9.41	Netherlands	53613	60.18
Paraguay	13688	15.78	Austria	54121	45.24
Armenia	14193	17.69	U.S.A.	63670	76.99
Brazil	14592	16.66	Norway	65662	105.33

Table 1.2.3. - *Per capita* gross domestic product and energy consumption for selected countries

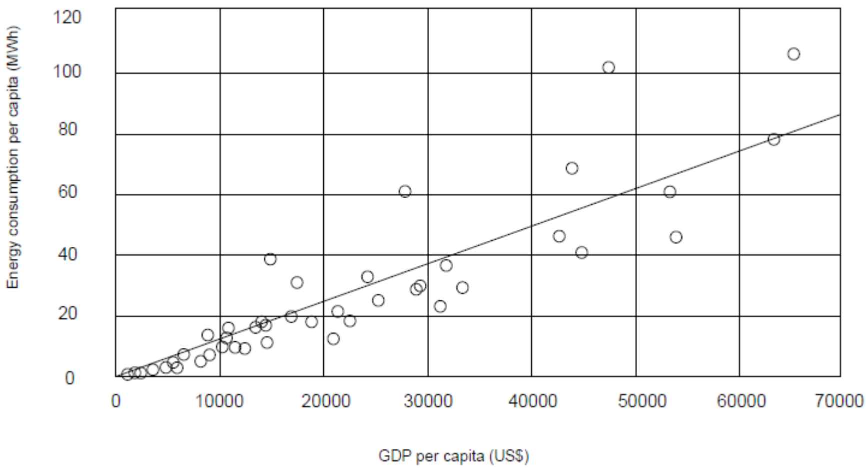

Figure 1.2.1. - *Per capita* gross domestic product and energy consumption for selected countries.

Also, if the human development index defined by the United Nations Development Program which takes, as significant parameters, life expectancy, *per capita* GDP, adult literacy, and school enrolment, is considered, again a correlation with *per capita* energy consumption is observed, as shown by the data of Table 1.2.4 and the plot in Figure 1.2.2 (Bryant, 2017).

COUNTRY	HDI	Energy *per capita*	COUNTRY	HDI	Energy *per capita*
		MWh			MWh
Niger	0.400	0.41	Colombia	0.752	11.15
Guinea	0.465	0.68	Iran	0.774	38.3
Uganda	0.525	0.77	Thailand	0.800	19.43
Tanzania	0.549	0.91	China	0.768	30.77
Cameroon	0.576	1.59	Mexico	0.758	17.52
Sudan	0.508	2.32	Costa Rica	0.809	11.96
Nigeria	0.535	2.55	Argentina	0.842	21.33
Ghana	0.632	3.48	Uruguay	0.809	18.32
Nicaragua	0.667	4.26	Bulgaria	0.795	32.22
Bangladesh	0.661	2.83	Chili	0.855	24.46
India	0.633	6.81	Russia	0.822	60.27
Filipinas	0.699	4.79	Panama	0.805	27.07
Guatemala	0.627	5.71	Greece	0.887	28.96
Iraq	0.686	13.27	Turkey	0.838	22.82
El Salvador	0.675	7.08	Slovakia	0.848	35.84
Tunisia	0.731	9.52	Hungary	0.846	29.25
Vietnam	0.703	12.38	New Zealand	0.937	45.91
Ecuador	0.740	11.92	South Corea	0.925	67.33
Argelia	0.745	15.91	France	0.903	40.46
Egypt	0.731	9.64	Canada	0.936	100.74
Perú	0.762	9.41	Netherlands	0.941	60.18
Paraguay	0.717	15.78	Austria	0.916	45.24
Armenia	0.759	17.69	U.S.A.	0.921	76.99
Brazil	0.754	16.66	Norway	0.961	105.33

Table 1.2.4.- Human development index and *per capita* energy consumption for selected countries

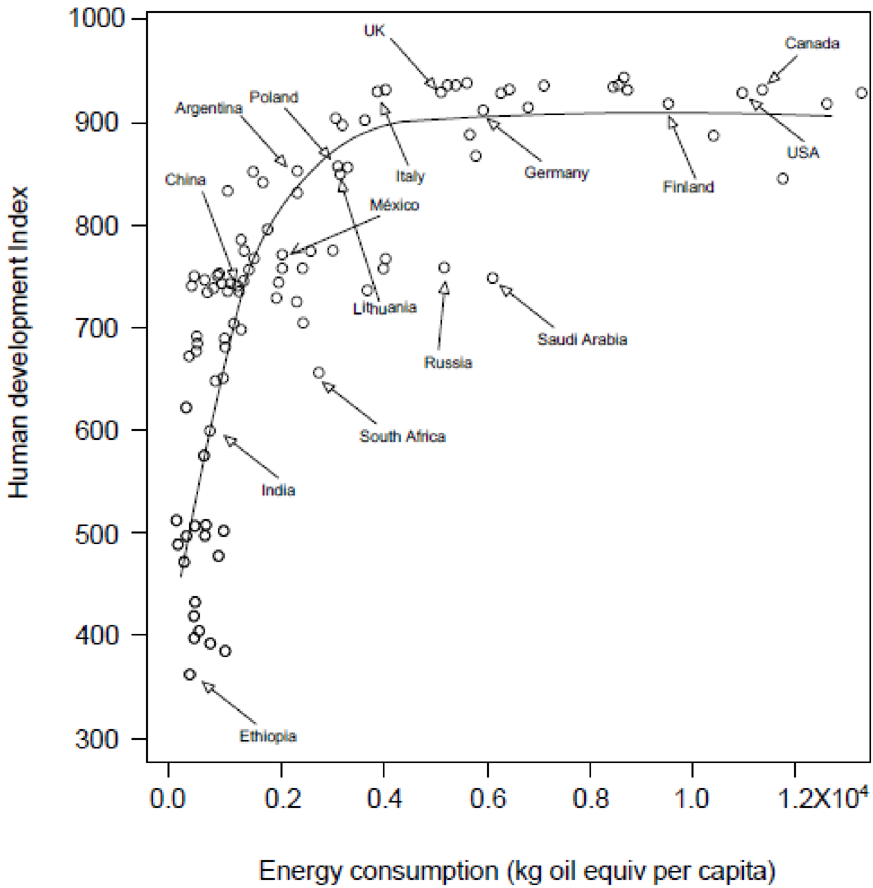

Figure 1.2.2. - UNDP Human Development Index vs energy consumption *per capita* (Bryant, 2017).

1.3 Primary energy sources

Since prehistory until the mid-17th century, primary energy sources were employed with two goals: generation of heat or energy production for mechanical applications. Heat was almost exclusively provided by burning wood and mechanical energy was obtained from muscle effort of men and animals, except for a small fraction received from wind or water flow and that was employed in powering mills and in boat propulsion.

The advent of the steam machine and the efficiency and cost advantages of coal with respect to wood, determined that huge efforts were devoted to coal mining and, by 1850, coal surpassed wood in the global energy market. By this time commercial production of oil began and, some 50 years later, its share in the energy market was already significant.

Two events must be pointed as critically boosting energy consumption. The first one was the introduction, by mid XIX century, of the electric generator, a device that allows the conversion of mechanical energy into electricity, which led to the use of turbines in hydroelectric and thermal utilities. Thermal electric plants increased the coal demand and, also, opened the market for the use of natural gas in lighting and heating devices.

The second event that modified primary energy consumption trends was, by the end of the 19^{th} century, the introduction of the internal combustion machine which ushered the expansion of the automotive industry with the production of large numbers of cars and trucks motorized by fuels obtained from oil.

In the 20^{th} century's second half, nuclear power plants began to provide electricity at commercial scale, and in the last decades solar and wind power have entered the energy market with significant shares. Solar and wind, with hydroelectric plants, are the so-called renewable energies, since no finite resources are consumed by them. Anyhow, the use of renewable primary sources is still low, and the world total energy demand is currently provided mainly by fossil fuels (coal, oil, and natural gas) which, in 2022, accounted for 80% of the 600 EJ total demand. Figure 1.3.1 presents the evolution of the consumption of different primary sources since 1800, while in Table 1.3.1 the contribution of each primary source in 2022 is shown, according to data published by the International Energy Agency (IEA) (International Energy Agency,2023). Looking into the future, and considering the need that an increasing energy demand will need to be satisfied, a couple of critical questions must be answered: a) what is the amount of energy that can be yearly provided by each primary source? b) for how many years can this yearly provision be sustained?

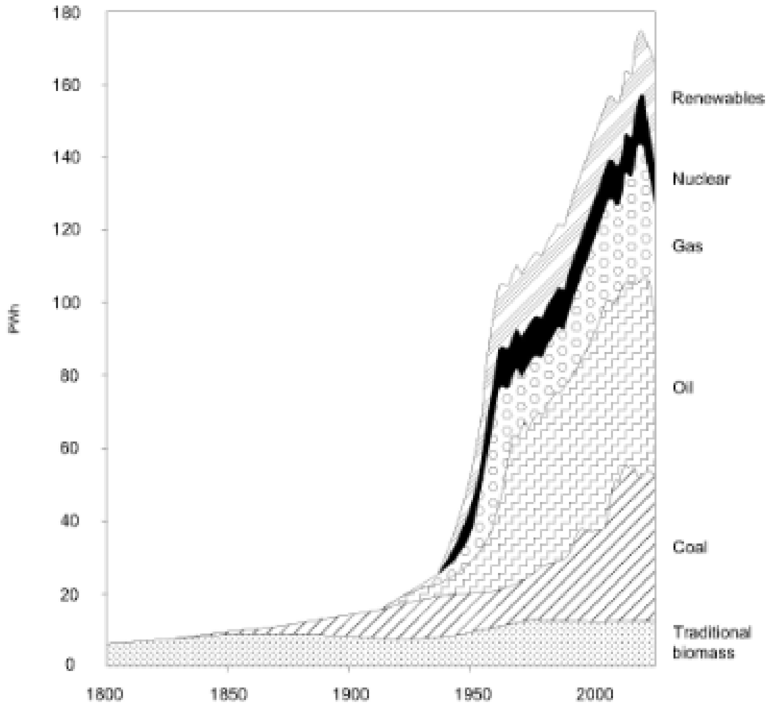

Figure 1.3.1. - Market share of different primary sources in the energy market for the 1800 – 2020 period.

Primary source	Share (%)
Biomass	10.1
Coal	26.9
Oil	29.6
Natural gas	22.9
Nuclear	4.6
Hydroelectricity	2.6
Wind	1.3
Solar	1.1

Table 1.3.1. - Market share of primary energy sources in 2022

1.4 Comments on the analysis of the contribution of a primary energy source

It is important to notice that consumption values given in the preceding section correspond to the amount of energy delivered by each primary energy source, which differs from the amount of energy effectively employed by the final user. Thus, according to data for the year 2022 given by the IEA (International Energy Agency, 2023), energy delivered by primary sources amounted to 632 EJ while net consumption by final users was 442 EJ, which implies a 30% loss.

Such a difference is due, in part, to the energy employed in sustaining the processes involved in exploiting the primary source, such as pumping oil from the well, building a pipeline or a windmill, etc. Also, there are energy losses in the processes that carry energy from the primary source to the final user: oil spills, energy losses in electric conduction over large distances, oil processing in refineries, etc. In order to account for these facts, the concept of Energy Received Over Energy Invested (EROI) has been defined as the quotient:

$$EROI = \frac{Energy\ Received}{Energy\ Invested}$$

Thus, the use of a particular primary source will be attractive if the EROI value is sensibly larger than 1. By the same token, a crucial point is the efficiency with which the final user employs the received energy: an internal combustion engine actually employs less than 30% of the energy produced by fuel burning, and the efficiency of a state-of-the-art thermal plant for electricity generation from natural gas is, at most, 50%.

Another important point that should be considered is the energy market evolution trends. When evaluating market dynamics, the usual approach was to analyse the contribution of each primary source to the total energy consumption and the projected evolution of that share. One of the most cited papers on this issue (Marchetti and Nakicenovic, 1977), was based on the idea that the energy market evolution may be described as a Darwinian struggle among primary sources, which can be considered as biological species competing for their habitat. Thus, working on an *ad hoc* modified form of the logistic substitution equations of mathematical biology, these authors could satisfactorily fit historical data up to 1970 and, projecting the obtained curves, concluded that the market share for oil would have a maximum value by 1985, when its substitution by natural gas and nuclear energy would occur. According to their approach, in 2020 natural gas and nuclear energy would have, respectively, 50% and 15% of the market share. Obviously, these predictions have been proved to be wrong as data from Table 1.3.1 show: oil share is still larger than that of coal and gas, and the nuclear market share is below 5%.

This analysis was reformulated (Terneus et al., 1997) on the basis that the driving force for the substitution process in the energy market is not the Darwinian struggle between primary sources, considered as competing species, but the specificity of market demand. In this approach, it was pointed out that options for final users can be classified according to a binary option: energy bought is received either as electricity or under non-electric forms. On this basis, the logistic substitution analysis showed that there is a continuous increase in electricity demand by final users and that this increase is independent of the primary source employed for attending it. With this consideration it was possible to describe the energy market evolution as a competence in which non-electric forms of energy delivered to the final user are substituted by electricity. On these grounds, historical data are satisfactorily correlated and, in fact, in 2022 electricity delivered accounts for 53% of total energy consumption by final users. Hence, any prospective analysis of market trends should be focalized on considering all the available ways of electricity generation. Table 1.4.1 displays IEA data on electricity generation with different primary sources (International Energy Agency, 2023).