The Energy Paradigm: Technology-Environment-Economics

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Energy has been the basis of economic prosperity of developing and industrialized nations in the last decades. The energy demand continues to grow steadily and replacement of fossil fuels by renewable sources is an issue for both, policy makers and the public. This transition will involve massive investments in research, technological development, and new processes. An overview of these factors is given in this study. Among scientific and engineering areas, Chemical Engineering will play a key role to obtain alternative liquid fuels with low CO_2 emissions, in a competitive economic environment.

KEYWORDS: World energy demand, CO_2 emissions, Sustainable energy processes, Renewable feedstocks, Hydrogen, Decarbonization.

La energía ha sido la base de la prosperidad económica de las naciones en desarrollo e industrializadas en las últimas décadas. La demanda de energía sigue creciendo de forma constante, y la sustitución de los combustibles fósiles por fuentes renovables es un problema tanto para los responsables políticos como para el público. Esta transición implicará inversiones masivas en investigación, desarrollo tecnológico y nuevos procesos. En este estudio se da una visión general de estos factores. Entre las áreas científicas y de ingeniería, la ingeniería química jugará un papel clave para obtener combustibles líquidos alternativos con bajas emisiones de CO_2, en un entorno económico competitivo.

PALABRAS CLAVE: Demanda mundial de energía, emisiones de CO_2, Procesos energéticos sostenibles, Materias primas renovables, Hidrógeno, Descarbonización.

INTRODUCTION

Richard E. Smalley (1943-2005), professor in Chemistry (Rice University, Houston, TX) and Nobel Prize Chemistry winner in 1996 for his discovery of fullerenes, in one of his last presentations listed the "Top ten problems for next 50 years", which in order of importance were: energy, water, food, environment, poverty, terrorism and war, disease, education, democracy and population. Energy, according to Prof. Smalley, is the key factor that might contribute to solve many of the other problems. In 2004, 220 million barrels of oil equivalent/day were used by the world, both as fuel and to generate electricity. According to Smalley's forecasts, by 2050, 400-500 million barrels of oil equivalent/day, some 40-50 000 TWh of primary energy will be needed [1]. Prof. Smalley's predictions, made in 2004, may have large deviations, since in 2020 already 26 800 TWh were consumed in electricity alone.

Energy consumption in developed countries is driven by three sectors: transportation, industry, and commercial and residential. Each consumes around 1/3 of the total energy. Currently around 80 % of the primary energy in the world comes from fossil fuels and only 19 % from renewable sources (hydraulic, solar, eolic and biomass) [2]. Renewable sources accounted roughly for the 29 % of the global production of electricity in 2020 [3]. Nuclear energy offers many advantages if the radioactive waste problem could be solved. It was questioned in many countries as a result of the Chernobyl accident in 1986, and although public perception had improved, the Fukushima accident in 2011, as a result of an earthquake and tsunami, made nuclear energy unpopular again. Nuclear plants were banned in Germany since 2011. Roughly, the world renewable energy consumption distribution is shown in Figure 1.

The recent Russian invasion of Ukraine has uncovered a fragile energy balance, particularly in Europe, due to its reliance on oil and natural gas supplies from Russia. The ongoing confrontation in Ukraine is having dramatic consequences in the lives of millions of human beings, affecting the environment, and having an unpredictable impact on the energy supply.

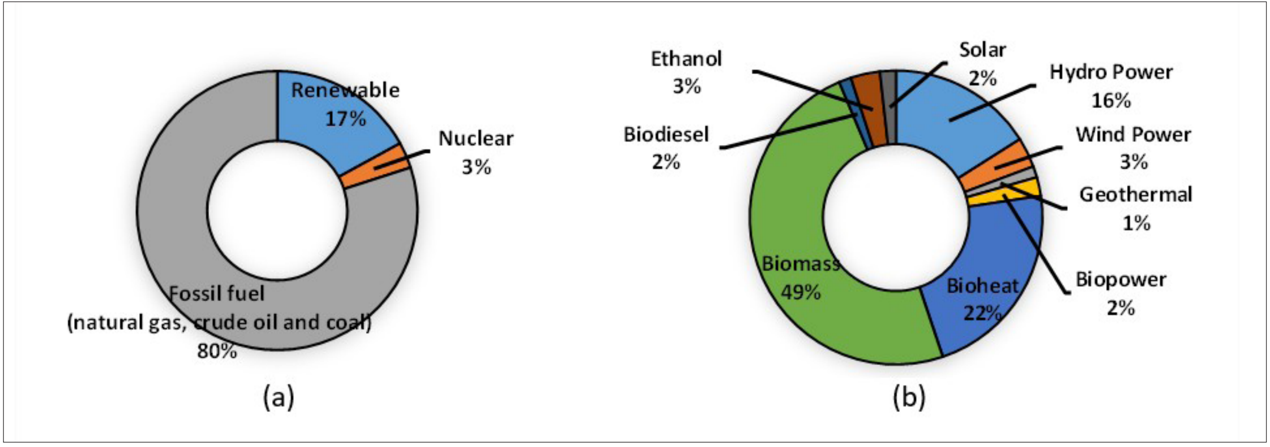
In recent decades, coal and nuclear power plants have been closed in Europe as part of the energy transition to renewable sources. However, it is currently impossible to avoid fossil fuels to meet the energy demand. The reduction in natural gas and oil supplies from Russia has caused an exponential increase in fuel and electricity prices in the European Union. It may lead to a deep economic recession.

The purpose of this article is to give an overview of the technical, environmental and economic factors involved in the challenges for the transition from fossil and nuclear fuels to noncarbon sources, with hydrogen as the primary energy carrier. The 2050 goal for a netzero carbon Europe and reduction of greenhouse gas (GHG) will have a big impact in the energy and the chemical industries. Chemical Engineering will play a fundamental role in the innovation and development of new technologies involving chemical, catalytic, photocatalytic, electrochemical and separation processes, that will contribute to achieve the netzero goals, in a competitive economic environment.

ENERGY SOURCES AND CONSUMPTION

Since 1950, fossil fuels have propelled the growth of the world's economies. Their extraction and combustion are a source of pollution. Coal is the cheapest and most important fossil fuel. Some 65 % of the estimated reserves are located in the United States, Russia and China. At the present level of consumption, coal could last about 200 years. Current oil reserves could be exhausted in 40-80 years, around 2059, that is, 200 years after the first oil well was drilled. Natural gas reserves could also last 40-80 years. Unconventional, higher cost, reserves would extend the availability to 200 years.

FIGURE 1. (a) World energy consumption, based on [2] and (b) Renewable energy consumption, based on [3]



The chemical industry's feedstocks have been influenced by war conflicts. From the beginning of the 20th century until 1950 (era of World War I), the raw material in the chemical industry was acetylene (obtained from coal). Since 1950 (era of World War II) acetylene was displaced by the more economical ethylene (obtained from cracking of petroleum). In the 21st century, the chemical industry has diversified its feedstocks, and the term biorefinery has been introduced [4]. The recent events in Ukraine have accelerated the use of renewable feedstocks for the chemical industry and power generation, so that Europe will be more rapidly independent of fossil fuels. This shift to renewable and clean energies increases the cost of energy.

ENERGY GENERATION AND THE ENVIRONMENT

The world's consumption of primary energy reached 612 QBtu in 2019, growing at 1.6 % per year since 2010, and a cumulative 47 % since the beginning of the 21st century. Table 1 shows the breakdown of the world's 2019 primary consumption by type of energy source and their use in the generation of electricity. Fossil fuels are the source of 84-85 % of this energy. Some 6 % is generated from hydroelectric plants, 4 % from nuclear reactors, and 5 % from renewables, which include solar and wind generation, geothermal, ethanol, biodiesel and other biofuels and wood chips.

Coal and natural gas generated 60 % of the World's 2019 electricity. The nuclear generation has remained fairly constant since the turn of the century. 2654 TWh were already generated from nuclear reactors in 2001. Although renewable sources show a 12-fold growth since 2001, their contribution to the world's energy mix is still only 5 % of the total.

EMISSIONS AND OTHER ENVIRONMENTAL FACTORS

All sources of energy cause some environmental impact. It is the job of engineers to reduce it; particularly, chemical engineers are best suited to diminish the impact of combustion processes. The use of fossil fuels as a source of energy is opposed by those who believe that greenhouse gases cause global warming. Although clean technologies do not directly emit CO_2, they also have considerable impact on the environment.

Fossil fuel emissions – Greenhouse gases

Water vapor and CO_2 are the main emissions in the combustion of fossil fuels. Water's presence in the atmosphere is 20-50 times that of CO_2, making it the most important GHG. The annual water evaporation and condensation cycle involve 2 400 000 QBtu [5], almost 4 000 times the world's annual primary energy consumption. Raising the temperature of the troposphere by 1 °C requires only 3 500 QBtu. CO_2 concentration is only 0.04 %. In 2019, there were about 3 400 Gt of CO_2 in the atmosphere. Fossil fuel CO_2 emissions that year were only 1 % of this content.

Many scientists link the increase in CO_2 to burning fossil fuels. The data show no conclusive correlation. The ratio of the measured increment of CO_2 to the CO_2 emissions in the 1965-2020 period varies from 0.25 to 1.12. In several years, the annual increment in measured CO_2, in Gt,

TABLE 1.

WORLD ENERGY CONSUMPTION AND ELECTRICITY GENERATION IN 2019 [2]

SOURCE	PRIMARY			ELECTRICITY	
	EJ	QBtu	%	Primary consumption (QBtu)	Electricity generation (TWh)
Oil	191.5	202.0	33.0	8.6	825
Coal	158.8	167.5	27.4	106.4	6298
Natural gas	138.7	146.3	23.9	49.2	9824
Hydroelectric	37.3	39.4	6.4	39.4	4222
Nuclear	24.9	26.3	4.3	26.3	2796
Renewables	29.0	30.6	5.0	30.6	2806
Total	580.2	612.1		260.5	27005
Total from fossil fuels	489.0	515.8	84.3	164.2	16497

decreases even as the emissions increase. A graph of the quarterly data of the emissions and the annual increase in atmospheric CO_2 shows this lack of correlation (Figure 2). The atmospheric concentration exhibits its seasonal variability, while the emissions continue steadily [5].

Other GHG are emitted in smaller amounts when burning fossil fuels. Their concentrations tend to be bellow parts per billion. Methane is associated with fossil fuels because of the fugitive emissions in the handling of natural gas and petroleum-associated gases. These emissions are only the 5th most important source of methane. Its importance as a greenhouse gas is artificially derived from its "Global Warming Potential (GWP)". This value is calculated from a timelife equation and then integrated over a period of 100 years. There is no clear physical interpretation of the GWP [7].

Nuclear energy – Environmental factors

The generation of electricity from nuclear reactors does not directly produce CO_2 emissions. Its environmental impact derives from the mining of uranium and, more importantly, from the generation of nuclear waste. Great progress has been made in securing the *high-level spent nuclear fuel*, but resistance remains to the use of nuclear reactors in several industrialized countries.

Renewable Energy - Environmental Factors

Biomass

Biomass emits CO_2. It is considered carbon neutral if the cut down trees and crops are replaced with new plantings. Its most damaging impact on the environment is that it causes some form of deforestation. 29 billion gallons of crop-based ethanol were produced in the world, most in the US (54 %) and Brazil (30 %). The energy value of this ethanol is only 2.2 QBtu.

Wind and solar use of resources

Wind turbines and solar panels exhibit very low energy density, requiring vast use of land and other resources (Table 2).

Both, wind turbines and solar panels, also require more materials than fossil fuel-based power plants (Figure 3). Solar farms require almost 30 times more materials than natural gas combined cycle technology, and 14 times more than coal to generate

FIGURE 2. Quarterly CO_2 emissions and atmospheric content (Gt of CO_2) [6]

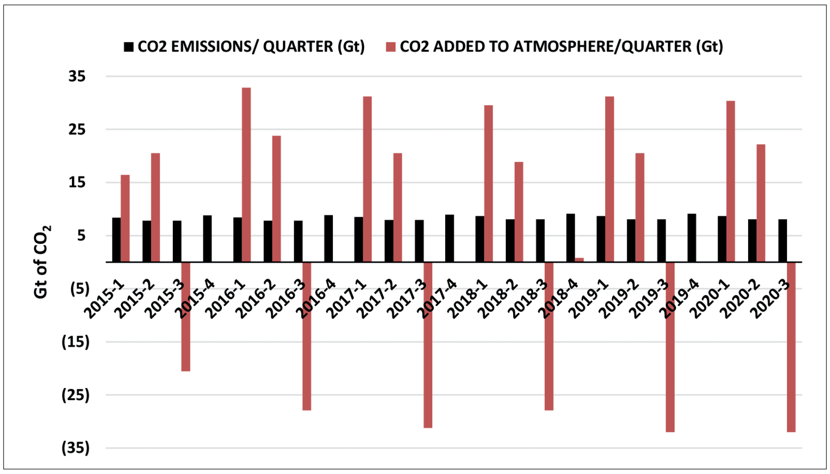


FIGURE 3. Materials requirements for electricity generation technologies [8]

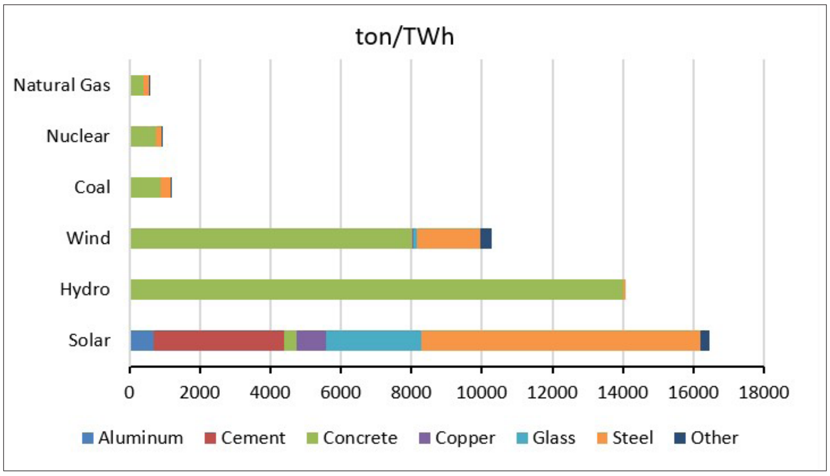
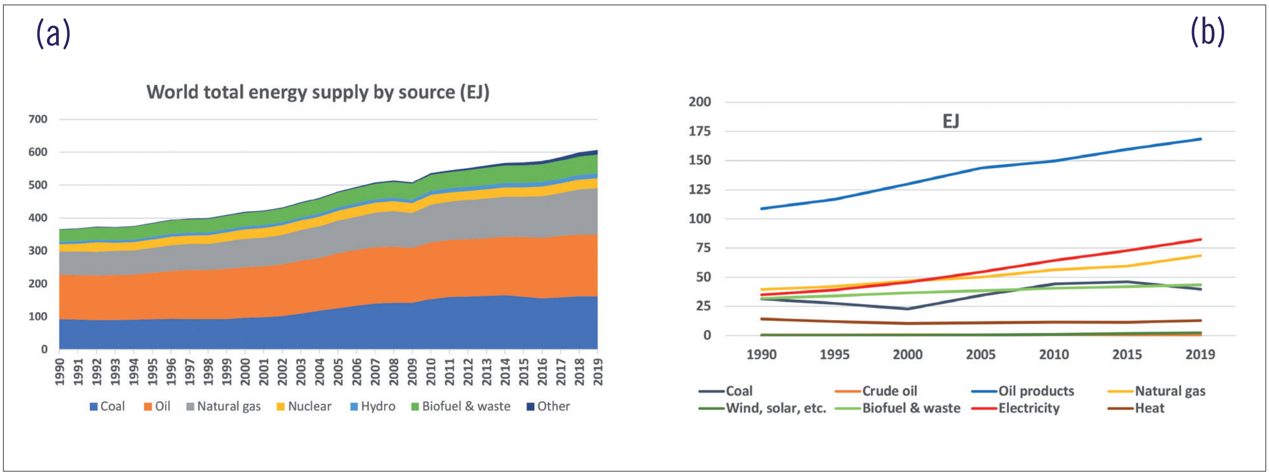


TABLE 2.

TYPICAL LAND USE INTENSITY FOR ELECTRICITY GENERATION TECHNOLOGIES [5]

Technology	Acres/MW of Nameplate Capacity
Natural Gas	0.10
Coal	0.40
Nuclear	0.65
Solar	8
Wind	80-140
*1 Acre≈0.41 hectares	

FIGURE 4. (a) Growth of world's total energy supply by source [9], (b) Growth of world's total final energy consumption by fuel [10]



a TWh of electricity (Figure 3). Wind uses 18 times more materials than natural gas and 9 times more than coal technologies. These estimates do not consider the substantial amount of copper and other materials required to connect the electricity to the grid.

The disposal of the broken fiberglass windmill blades, broken or inoperable old solar panels also presents environmental problems. A system will have to be designed to dispose of unusable batteries containing lithium, manganese, nickel, and cadmium, to minimize the damage to the environment. Large spent batteries with many cells must be safely handled since the residual charge can kill a person.

REPLACING FOSSIL FUEL-GENERATED ELECTRICITY

Like biomass, wind and solar sources are not yet economical when compared with the existing dispatchable alternatives. Wind and solar energy generation sources are both intermittent, they are non-dispatchable. They require full backup capacity generation from a fossil fuel or nuclear plant or a large number of backup batteries, currently expensive and unavailable.

The cost of implementing the green proposals will reach hundreds of trillions of dollars/euros, while thwarting industrial economic growth. The net effect of forcing the use of currently uneconomical "clean energy" generation sources is a higher cost of energy.

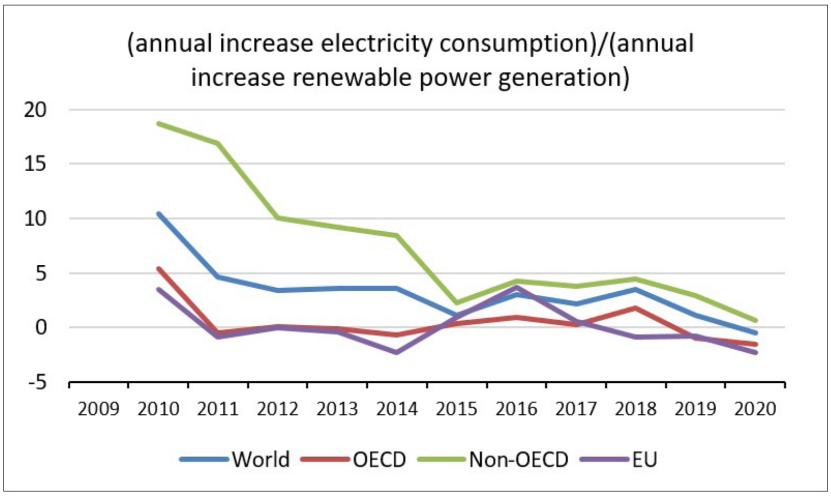
ENERGY CONSUMPTION AND DECARBONIZATION

Replacing fossil energy with nuclear and renewables is a difficult task. Fossil sources constitute more than 80 % of the total primary energy supply and continue growing as China, India and developing countries increase their industrialization (Figure 4a). Regarding final energy, electricity and natural gas consumption increased at close to 4 % and 2 % annually in the 1995-2019 period (Figure 4b). They are expected to continue growing in the near future.

The ratio of annual increase of total electricity consumption/annual increase of renewable generation measures the deployment of renewable sources, the lower the ratio the higher the rate. This ratio has changed in several regions of the world. The EU and OECD countries have already reached an acceleration stage (Figure 5).

Transport is the highest energy consumption sector and the one with the higher growth. As transport is more than 98 % based on fossil fuels, their replacement by renewable electricity remains a formidable task.

FIGURE 5. Ratio: annual increase of electricity consumption/annual increase of renewable electricity generation [11]



Only about 10 million of electrical vehicles were on the road in 2020 (Figure 6). Further efforts to reduce price, increase energy density of batteries and develop infrastructure is needed.

DECARBONIZATION AND TECHNOLOGY DEVELOPMENT

Heavy vehicles, aviation and industrial sectors depend on technologies that are under development. Fossil fuels are difficult to replace. Green hydrogen or synthetic fuels, produced from green hydrogen and captured CO_2, are promising alternatives.

Replacing fossil fuels in the iron and steel and cement and petrochemical industries require substantial developments. Carbon capture technologies in these industries are in their infancy.

CHEMISTRY AND CHEMICAL ENGINEERING ROLE IN ENERGY FUTURE

Chemistry and Chemical Engineering have made important contributions in converting fossil fuels into useful products. Chemical Engineering principles are used to generate electricity and to produce fuels and chemicals using nonrenewable feedstocks [13].

ENERGY AND CHEMICALS FROM BIOMASS

Technologies have been developed to convert biomass into electricity, transportation fuels and chemicals for the chemical industry [14]. Biomass rich in carbohydrates can be fermented to produce ethanol, currently used for gasoline-ethanol mixtures (Figure 7).

Municipal wastes, forest and agriculture residues and landfill gases can be used to generate electricity via mass incineration, gasification, pyrolysis and anaerobic digestion. Biodiesel can replace conventional diesel, and is made from vegetable oils, animal fat and recycled cooking oils (Figure 8).

SOLAR ENERGY

Solar energy can produce both heat

FIGURE 6. World total number of electric vehicles on the road [12]

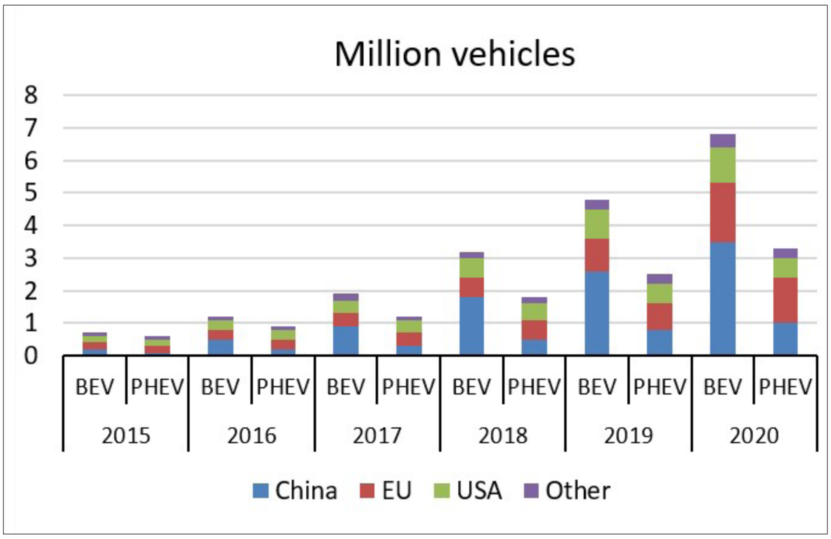


FIGURE 7. Chemicals from carbohydrates [15]

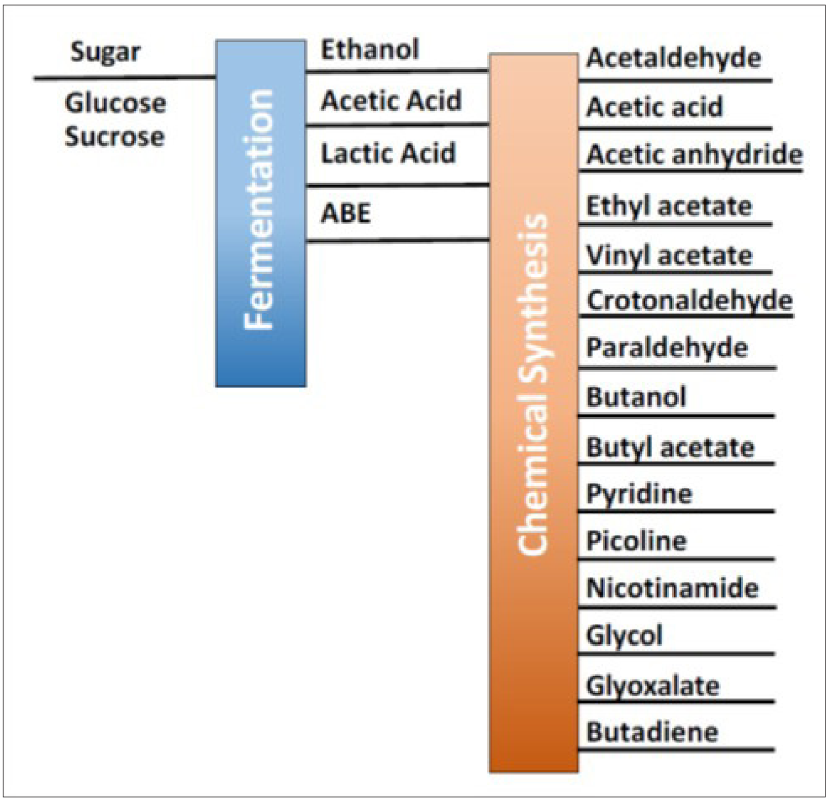
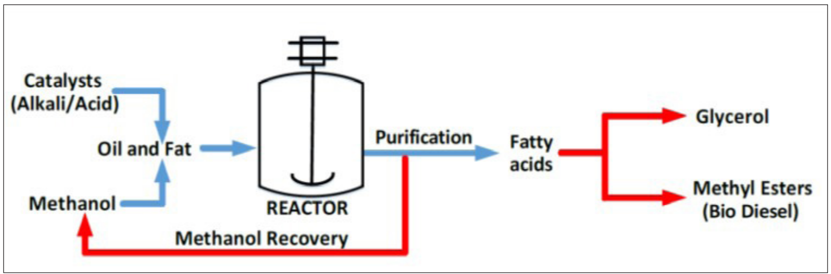


FIGURE 8. Process for the production of biodiesel



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and electricity for common uses and high-temperature electrolysis. It is the largest available resource, as it provides more energy in one hour to the earth than the energy consumed in one year. Solar energy utilization involves two steps: (i) capture and conversion and (ii) storage. This is accomplished by transforming light into electricity using semiconducting materials (photovoltaics). Chemistry and Chemical Engineering are playing an active role in this endeavor, developing new materials, catalysts, and fuel cells [16].

Fuel cells as an electrochemical energy conversion device, consume chemicals and electricity to produce other chemicals (H_2 by electrolysis, $H_2 + O_2$ to produce electricity, etc.). Attempts have been made to reduce CO_2 by electrocatalytic cells, and even using the heat from exothermic reactions with simultaneous electrical energy generation [17].

HYDROGEN

Hydrogen can be considered as a "clean fuel" since its combustion produces only water. It is currently obtained from coal and fossil fuels, but also from renewable resources (Figure 9). The use of hydrogen as fuel would reduce CO_2 emissions. Fuel cells provide efficient and clean electricity from different fuels. Catalytic processes have been explored by Prof. Dumesic at the University of Wisconsin-Madison, to produce H_2 from biomass and to convert plant sugars into gasoline [18].

SEPARATION TECHNOLOGIES

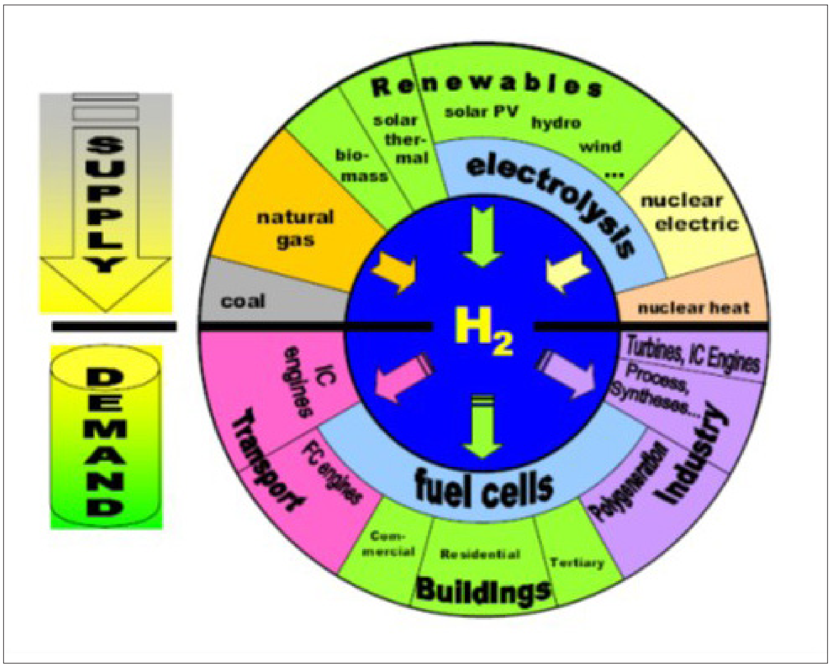
Biogas produced by anaerobic digestion contains typically 40-60 % methane (CH_4) and 40-60 % CO_2. The upgrading of biogas involves the separation of CH_4 and CO_2. It is carried out by technologies well known in Chemical Engineering: pressure swing adsorption (based on the difference in adsorption of the components), membrane separation (different molecular size and diffusivities, CO_2 will pass through the membrane, while CH_4 will not), and absorption with amines (the amines absorb CO_2 by chemical reaction, while CH_4 does not react).

CONCLUSIONS

Replacing fossil fuels with renewable energy sources will require important technological innovations in the chemical and energy sectors. Resources and raw materials must be diversified, and processes must be developed leading to more sustainable and still competitive chemical production systems. To make viable many alternatives, developed at laboratory scale, several goals must be fulfilled:

- Economic energy generation from renewable resources. Use of both electricity and H_2 as energy carriers.
- Electrification of the chemical industry.
- Production of H_2 by large electrolysis units and catalytic reactions from different sources. Replace fossil fuels by H_2 to reduce GHG and pollutant emissions.
- Catalytic processes and reactors to convert plant sugars into gasoline.
- Electrochemical CO_2 reduction to obtain, with H_2, olefins and aromatics.
- Effective separation and purification technologies (membrane technology and reactive-separation processes).

FIGURE 9. Hydrogen: primary energy sources, energy converters and applications [19]



Abbreviations

ABE: Acetone-Butanol-Ethanol blend, ratio 3:6:1
BEV: Battery Electric Vehicle
EJ: Exajoule – Quintillion Joules – 10^{18} Joules
EU: European Union
GHG: Greenhouse gases
GSR: Global Status Report
GWP: Global Warming Potential
OECD: Organization of Economic Cooperation and Development
PHEV: Plug-in Hybrid Electric Vehicle
QBtu: Quadrillion Btu – 10^{15} Btu
ton: 2000 pounds
TWh: Terawatt-hour – 10^{12} Watt-hour
Gt: Gigatonne - 10^{9} metric tons

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