Harvesting Alternate Energies from Our Planet

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Recent price fluctuations have focused attention on the phenomenal increase of global energy consumption in recent years. We have almost reached a peak in global oil production. Total world consumption of oil will rise by nearly 60% between 1999 and 2020. In 1999 consumption was 86 million barrels of oil per day, which has reached a peak of production extracted from most known oil reserves. These projections, if accurate, will present an unprecedented crisis to the global economy and industry. As an example, in the United States, nearly 40% of energy usage is provided by petroleum, of which nearly a third is used in transportation. An aggressive search for alternate energy sources, both renewable and nonrenewable, is vital. This article will review national and international perspectives on the exploration of alternate energies with a focus on energy derivable from the ocean.

INTRODUCTION

As late as 10 years ago, there were strong proponents on both sides of the debate about the reality of a rapidly approaching global energy crisis. Although all agree that the Earth's resources of fossil fuels are finite, the optimists believe that the resources will last for a very long time before a crisis is reached. The world's appetite for liquid hydrocarbon as an energy resource has continued to grow at an exponential rate. Global output, which was much less than a million barrels per day in 1900, has increased to 85 million barrels per day today, growing at a rate of 1.5–2.0% per year. This supply is rapidly failing to meet the demand, as reflected, in part, in the rapid rise and unprecedented fluctuations of the price of petroleum. Of all the energy sources upon which the global economy and industrial growth are built, the prominent sources are petroleum, coal, natural gas, biomass, hydroelectric, and nuclear.

A seminal paper, published in 1956 by an American petroleum geologist, M. King Hubbert,[1] now popularly known as "Hubbert's peak," was highly criticized at the time by his peers. Utilizing a statistical model, Hubbert predicted that the production of oil would reach a peak in the lower 48 states of the United States, after which it would diminish. Figure 1 illustrates Hubbert's prediction superimposed with the actual data since his publication.

How would you…

…describe the overall significance of this paper?

An aggressive search for alternate energy sources, both renewable and non-renewable, is vital. This article will review both national and international perspectives on the exploration of alternate energy with special focus on energy derivable from the ocean.

…describe this work to a layperson?

We have almost reached a peak in global oil production. Total world consumption of oil will rise by nearly 60% between 1999 and 2020. These projections, if accurate, will present an unprecedented crisis to the global economy and industry. As an example, in the United States nearly 40% of energy usage is provided by petroleum, of which nearly a third is used in transportation.

Validation of the accuracy of this model has led to a critical evaluation by a number of agencies, including the U.S. Department of Energy (DOE), to predict a global peak in production. A Saudi oil geologist, S.I. Al Husseini, reported the results of his study over 10 years of the 250 major oil fields that provide most of the world's oil. Since 2004 the production from these fields has reached a plateau of 85 million barrels of oil per day. This flat production rate, he claims, may last as long as 15 more years, after which there will be a gradual decline, suggesting that the world has already reached a peak in production. This projection is consistent with those of the head of the French oil company, Total, and the chief executive officer of Conoco Phillips. To meet the increasing demands by 2010, they project that nearly 40% of the daily oil needs will have to come from either untapped or undiscovered oil fields. Table I illustrates the rate of world oil consumption since 1975 and projected to 2015 in the industrialized, Eastern European, and developing nations. The figures clearly indicate that the rate of increasing demand from developing nations, primarily China and India, outpaces those in the other regions.

ALTERNATE ENERGY SOURCES

Conserving energy through improved technologies, such as hybrid automobile engines, use of electric power and hydrogen, and improved turbine designs, would assist in reducing fossil fuel consumption rates. However, these developments will be slow in coming and will not offset the projected

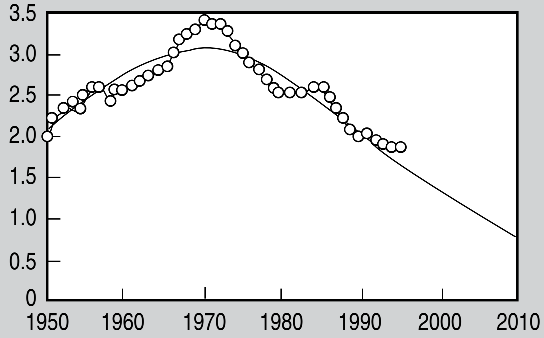

Figure 1. The prediction of total oil production (billions of barrels per year) in the lower 48 states of the United States with actual production superimposed.

global growth rates of energy consumption.

Alternative energy resources can be broadly divided into two groups: renewables and non-renewables. The renewables include biomass, hydrogen, wind, nuclear fusion, solar terrestrial, ocean waves and tides, geo- and ocean-thermal, hydroelectric, and synthetic fuels. Some of these approaches are limited by geographic locations and economic factors. These include geo- and ocean-thermal, hydroelectric, waves, and tides. Other resources are actively pursued by many countries to produce various forms of hydrocarbons for use either as additives to the existing fossil fuels or as a fuel substitute. The non-renewables predominantly include clean coal, nuclear fission, synthetic gas, oil shales, and methane hydrates. The innovative technology demands and cost factors associated with effective utilization include sequestration of gaseous and solid byproducts, radioactive waste disposal, and environmental issues.

Biomass

Energy extracted from biomass dates back to very early human activities, with the discovery of fire, and continues to be the world's fourth-largest energy source, providing 5×10^{19} joules per year. This energy source is currently derived from agricultural waste, forestry waste, municipal solids, industrial waste, and energy crops. The goal in the United Sates, reported by the National Renewable Energy Laboratory of the DOE,[2] is that by 2020, 10% of transportation fuels, 5% of electric power production, and 18% of chemicals and materials will be provided from biomass sources. Research and development efforts are underway to maximize biomass-derived methanol, ethanol, and diesel from sugar cane, cassava, soybeans, corn, jatropha, miscanthus, and switch grass, amongst others, with claims of ethanol production varying from 3,300 to 14,000 liters per hectare.[3] Liquid hydrocarbon production from sugar cane has been successfully demonstrated by Brazil. The crop is confined to specific tropical and equatorial regions of the world, providing a limited supply either as a substitute for or as an additive to petroleum. In the United States, major efforts are in progress to augment petroleum with as much as 10–15% ethanol derived from corn. This effort has led to numerous controversies, including:

- Higher energy cost for corn production and conversion to ethanol
- The energy equivalent of one liter of gasoline requires 1.5 liters of ethanol
- To provide 10% of all auto and truck transportation fuel needs from ethanol will require about 8×10^7 hectares of agricultural land to be removed from food production
- The hygroscopic property of ethanol will contribute to accelerated corrosion in fuel containers and potential ice formation when the fuel is exposed to lower temperatures
- Ethanol has a significantly lower flash point than JP5 and JP8 jet fuels

The most controversial debate on ethanol production concerns the use of grain as feedstock. The energy requirement for growing the corn, harvesting it, transporting it, and manufacturing the ethanol versus the energy content of ethanol has been the center of this controversy. A number of papers have been published suggesting that the net energy value, which is the energy content of ethanol minus the fossil energy used to produce ethanol, varies from -9.4×10^6 joules per liter to 8.5×10^6 joules per liter.[4] Table II provides the energy content of various biofuels in comparison to regular unleaded gasoline and diesel fuel.

Material challenges for biomass fuel substitutes include the requirement for corrosion-resistant materials such as stainless-steel- or titanium-based alloys and antifouling paints. Biodiesel, extracted from sources such as vegetable oils, animal fat, and recycled oil, presents yet another set of challenges for fuel usage and materials, including moisture uptake, tank corrosion, degradation during prolonged storage, biofouling, poor lubricity, decreased energy per liter, and gelling at low temperatures. The technological challenges are easily resolved by use of appropriate existing materials and additives. Biodiesel has the potential for recycling vast amounts of recyclable oils and animal fats. (In the United States alone 19×10^9 kilograms of animal fat are produced per year.)

Hydrogen: A Clean Energy Source

Some of the major advantages of hydrogen as an energy source include its abundance, high energy content per mass, environmental neutrality as an energy source, excellent flammability, flame speed and auto ignition temperature, and potential for use in fuel cells. Hydrogen can be derived from sources such as biomass, electrolysis using energy from hydro, wind, solar, or nuclear, and, with appropriate carbon sequestration, from oil, coal, and natural gas.

Three of the most viable approaches to hydrogen production are steam reforming of methane, the use of electricity to produce hydrogen from water, and the gasification of coal. Recognizing the shortage of CH_4 and its rapidly increasing cost, large-scale production of hydrogen by this approach would be prohibitive. For electrolysis, there will be a need to use 3.9 kWh of electrical energy to produce 1 m^3 of hydrogen that will provide an energy value of 3.2 kWh (80% efficiency). Coal gasification is a well-known commercial process and has been in the marketplace since 1970. Coal is an attractive hydrogen feedstock because of its abundance in the Earth's crust and coal mining infrastructure already in place with a price structure that is low and non-volatile. The major challenge in hydrogen production from coal would be to sequester carbon dioxide. One possibility is the use of deep saline aquifers with good top seals that are estimated to be able to store as much as 4.5 × 10^{13} kilograms of carbon.[5]

Apart from nuclear energy sources, a number of energy harvesting technologies could be considered for production of hydrogen. Utilization of the sun's energy by photonic processes is extensively being examined, utilizing organic and inorganic photovoltaic materials. The peak solar flux on Earth is about 1,000 W/m^2 with an average (considering day, night, and solar angle) of 200 W/m^2. With the current conversion efficiency of about 6%, the solar field required to produce the necessary amount of hydrogen to replace liquid hydrocarbon transportation fuel alone would cover 1 × 10^7 hectares.[6]

The DOE, along with the European Union countries, has embarked on the challenge of what is known as the hydrogen economy. This activity has been identified for development in several phases. The first phase consists of developing the technology needed for hydrogen power and transportation systems for selected locations; the second deals with market penetration and commercialization; the third, development of large-scale infrastructure; and the fourth, development of a national and international infrastructure. The critical path for developing a hydrogen economy has been targeted by the DOE based on performance and cost reduction. The targets are 2–3× performance increase for lightweight compact hydrogen storage, 4× cost reduction for hydrogen production compared to conventional fuels, and 10× cost reduction in carbon sequestration. All of these challenges or targets create significant needs for advanced material development. Among those needs are, for example, for distribution pipelines, use of expensive ferrous and titanium alloys immune to hydrogen embrittlement, effective metal in combination with fiber-reinforced composite tanks for hydrogen storage at 69 MPa, development of high-temperature materials for effective engine performance in ground transportation systems, and enhanced performance of hydrogen sensors for leak detection. (Irrespective of improved pipelines and hydrogen delivery at pumping stations, it is estimated that 1–3% of hydrogen will leak into the atmosphere. Extensive leakage will cause hydrogen escape into the troposphere that will deplete the OH that serves as a scrubber of atmospheric contaminants and greenhouse gasses.)

One of the major materials challenges is to safely store hydrogen. Apart from storage of hydrogen under pressure in sustainable containers, three major approaches are under consideration for hydrogen storage: reversible metal hydrides, non-reversible chemical hydrides (hydrogen carriers), and advanced adsorbent materials. The key challenges are lowering of desorption temperatures, improving kinetic response, and providing proper heat management during refill, decreasing regeneration costs, improving volumetric capacities, and developing manageable desorption temperatures. Metal hydrides appear to provide the highest percentage of hydrogen weight fraction in $Mg(BH_4)_2(NH_3)_2$ and $Mg(BH_4)_2$ with 12% hydrogen weight fraction. However, these compounds require ~350°C for hydrogen release. The targets for advanced material development are to optimize storage capacity at low hydrogen uptake and release temperatures, while maximizing the life cycle (durability) and minimizing costs.

Table I. The Rate of World Oil Consumption Since 1975 and Projected to 2015 in the Industrialized, Eastern European, and Developing Nations*

Region	1975	1985	1995	2005	2015
Industrialized	38.0	35.5	42.5	48.0	53.0
EE/FSU	8.5	11.0	6.0	7.5	9.5
Developing	8.0	13.0	21.0	32.0	43.0

* in million barrels per day

Table II. Gasoline Equivalents

Fuel Type	MJ Per Liter	Liter Equivalent
Gasoline, Regular Unleaded, (typical)	32	1.00
Gasoline, Reformulated (10% MBTE)	31	1.02
Diesel (typical)	36	0.88
Methanol (M-100)	16	2.01
Ethanol (E-100)	21	1.50
Biodiesel (B-20)	36	0.88

Additionally, it is important to recognize that hydrogen at 69 MPa pressure has 1/5 the energy density of gasoline. Liquid hydrogen increases the ratio to 1/4.[6] Before hydrogen can be used widely for various energy applications, its wide limits of flammability, low spark ignition energy, nearly invisible combustion flame, and high cost of pipelines (4 × 10^5 euros per kilometer) would continue to pose serious challenges.

Coal to Liquid

Another technology that is being heavily pursued is the production of liquid fuel from coal using the well-known Fischer–Tropsch process.[7] The process primarily consists of gasifying coal and using the water gas shift reaction to produce appropriate concentrations of carbon monoxide and hydrogen using conventional catalysts such as iron-, cobalt-, and nickel-based powders at modest temperatures of 150–200°C and modest pressures of about 1 MPa. The process provides gasoline and diesel fuel and, depending on the pressure temperature combination, CH_4. However, the process produces excess carbon dioxide and, based on the chemistry of the coal used, various other pollutants. Since the invention of this process at Kaiser Wilhelm Institute in the 1920s, it has been significantly improved by Sasol in South Africa, which is in the process of exporting the technology to China with a production capacity of 80,000 barrels of oil per day. The process is now being extended to use biomass and natural gas as feedstocks.

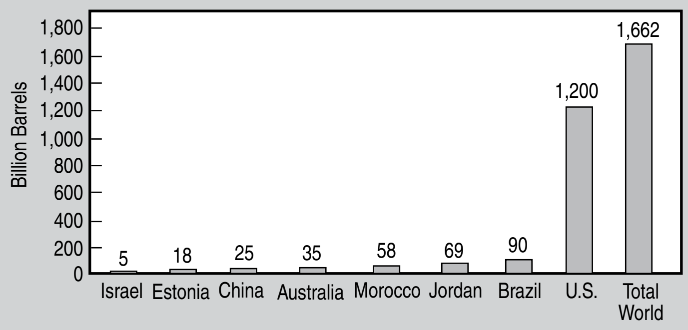

Figure 2. Major world oil shale reserves.

Oil Shales

Sedimentary rocks called oil shales contain significant amounts of hydrocarbons and are distributed world wide including in countries like the United States, Australia, China, Sweden, and Estonia. There are also known deposits in France, Germany, Brazil, Mongolia, and Russia. Figure 2 illustrates the global distribution of oil shale.

By far the largest deposit, consisting of more than 70% of the world reserves, is located in the Green River Basin of the Colorado River, covering parts of Colorado, Utah, and Wyoming. The total reserve is estimated to be in excess of 1,500 billion barrels of oil.[8,9] Pyrolizing the oil shales can transform kerogen based oil into synthetic crude oils. The organic matter in the oil shale contains an atomic ratio of hydrogen to carbon at approximately 1.5 to 3 times higher than coal.[10] This reserve is significantly greater than the proven estimate of world crude oil reserve. The conventional methods of extracting crude oil from oil shales include surface and underground mining. There are two technologies utilized for extraction of oil. The retort process involves heating the shale in an oxygen-free environment at temperatures between 450°C and 500°C, which decomposes the kerogen into gas, oil, and solid residue. The in situ decomposition process involves heating the deposit underground and subsequently extracting the oil and gas from the decomposed product. Current costs for extracting a barrel of oil from oil shales are estimated to be from $40 to $60 per barrel. There are a number of aspects that have significant environmental impact, including acid drainage, sulfur gas emission, atmospheric pollution, demands for water and electric power, disposal of spent materials and arsenic-bearing chemicals in the leach deposits, the need for hydrogen for upgrading the chemistry to produce suitable hydrocarbons, and regulating carbon emissions to meet regulatory standards.[11] Over the last 80 years, Estonia has met most of its energy demand with oil shales.

Tar Sands

Tar sands, often referred to as bituminous sands or oil sands, exist in many countries, with exceptionally large quantities in Canada and Venezuela.[12] Extraction of oil from tar sands has been performed for nearly 200 years and has been used to obtain coal gas for heating and lighting.[13] Other countries with reported deposits include the United States, Middle Eastern countries, Russia, Canada, and Venezuela. More than 40% of the Canadian oil production in 2007 came from tar sands.[14] The estimated reserves in Canada are about 1.7 trillion barrels, about 20% of which is exported to the United States. Most of the Canadian deposits are in northern and northeastern Alberta. Although the extraction of crude from tar sands is much simpler than extraction from oil shales, crude from tar sands is usually too heavy for pipeline transportation as is and is currently transported by pipeline only after an emulsification process with 30% water. The crude has very high sulfur content and presents challenges in terms of environmental concerns, including disposal of toxic chemicals, wastewater drainage to rivers, and carbon dioxide emission, as well as deforestation. Two tons of tar sands produce one barrel of oil with an extraction of about 75% of the bitumen. Ample availability of water, about 3 to 4 times in volume for each unit of crude oil, is a requirement for oil synthesis.[15] Table III provides a comparison of the principal factors influencing the extraction of crude oil from tar sands and oil shales.

Wind Energy

The extraction of energy from the wind is well developed and currently provides over 90 gigawatts of energy worldwide,[16] amounting to less than 1% of the world's electricity consumption. Countries such as Spain and Denmark have been aggressively engaged in wind power. As recently as during the last five years, European countries, the United Kingdom, and China have led the world in developing offshore wind power, particularly in the areas of the North Sea and the Baltic Sea.[17] In terms of wind power capacity, the United States leads the world at nearly 17 megawatts in 2007.[18] The effective usage of wind power is highly location-dependent, requiring wind speeds in excess of 7 meters per second, usually only available in high elevation or offshore locations. Although this technology is growing rapidly, it comes with a number of problems, such as connectivity to the existing grid, or utilization to store energy on location as hydrogen by electrolyzing water. The grids have to be designed to carry excess electric loads during high winds. Other problems relating to large wind farms, particularly those located near urban regions, are that they contribute to radar clutter for the aviation industry, requiring stealthy wind turbine design. Additionally, concerns have been ex-

Table III. Comparison of Principal Factors Influencing Economics of Producing Crude Oil

Characteristic	Tar Sands	Oil Shale
Reserves	>1 trillion bbl	>1 trillion bbl
Grade (Richness)	25 gallon bitumen / ton	25 gallon kerogen / ton
Hydrogen Content	10.5%	11.8%
N and S Removal	6.2 wt.%	4.0 wt.%
Loss to Coke	33 lb / ton of ore	Nil (burned for energy)
Net Yield of Oil	0.5 bbl / ton mined	0.58 bbl / ton mined

pressed about protection of wildlife, such as migratory birds running into the turbine blades and sea life from the acoustic noise. Enhancing the power production beyond 750 kilowatts to 2 megawatts per wind turbine requires improved turbine design with turbine blades greater than 100 meters long. These blades demand higher stiffness and resistance to fatigue and environmentally imposed degradation such as corrosion and stress corrosion, particularly for those installed offshore. Various approaches to resolve these issues are under consideration.

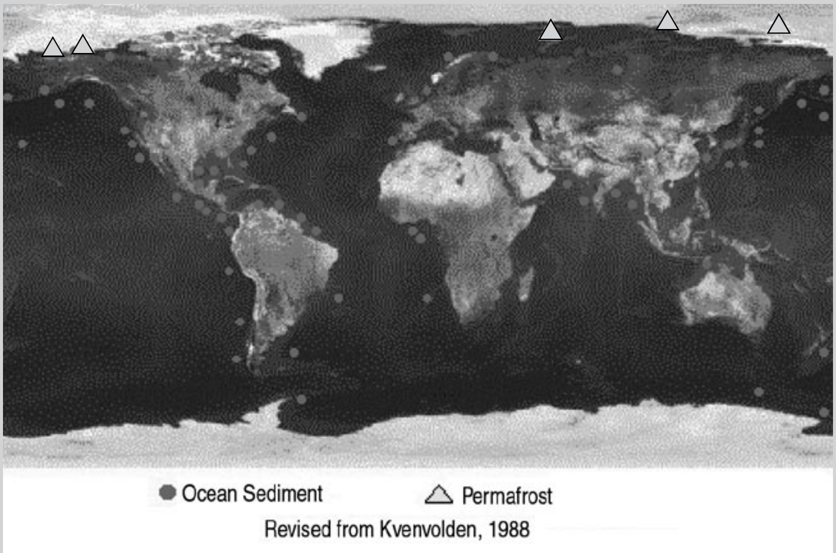

Figure 3. The locations of large methane hydrates deposits.

Ocean Energy

Extraction of energy from tides resulting from twice-daily variations in the sea level due to the gravitational effects of the sun and the moon, as well as from wave motion in the littoral regions of the seas, has been examined for potential energy production. Tidal energies can be efficiently extracted from only about 40 sites worldwide, which imposes significant limits for utilization. This approach, exploited by countries like France and Norway, is highly cost-intensive and imposes several environmental and navigational issues. Although the technology is well known, there are a number of materials-development challenges to enhance efficiency. Wave energy, on the other hand, has significant potential, although it is limited to specific coastal regions of southern parts of South America, Australia, and the United Kingdom. Several research projects in the United States, most prominently those supported by the Naval Facilities Engineering Command, are developing various test systems to produce 1 kilowatt from a single buoy. Although this technology has the potential of producing 50 kilowatts from a single buoy, the approach has a number of disadvantages that include serious operational problems during high sea states, impediments to coastal navigation and fisheries, and technological issues to reduce capital investment. Yet another approach to extracting energy from the ocean is to take advantage of regions where large thermal gradients exist between the surface water and deep water.[19] This effort is still in the research and development stage, primarily supported by the U.S. Navy to evaluate the efficiency of this approach and identify appropriate locations. Extensive studies in the United States and Japan are under way to develop a 10–12 megawatt ocean thermal energy system. The challenges for this approach confine energy extraction to equatorial and tropical regions of the ocean where the sea state fluctuations and ocean currents are not significant enough to disturb the energy extraction process. Materials for wide diameter pipelines to depths of nearly a thousand feet present a critical challenge to the stability of the surface platform, which would need to withstand abrasion, corrosion, and fouling. If successful, the generated power could either be directed to produce hydrogen or to provide electrical power for liquid hydrocarbon production through downscaled Fischer–Tropsch plants.

Solar Energy

Most of the Earth's energy resources, either in stored energy form in biomass, fossil fuel, and methane hydrates, or delivered each day from the sun, are derived from the sun's energy. The sun's energy impacting the Earth in a given day is equivalent to energy consumption over seven years. Conversion of solar energy to electricity using photovoltaic cells or solar energy concentrators has been the topic of keen research and development interest for more than 60 years. European countries, Japan, and the United States have led the development of photovoltaic technology for electricity production through the utilization of silicon-based solar cells. This technology is rapidly evolving to produce multi-megawatt systems in various regions of the world. Research is aggressively progressing in improving efficiency and cost by advancing thin photovoltaic technologies and solar energy concentrators. Organic photovoltaics have demonstrated significant improvement in efficiency over those of crystalline and amorphous silicon, although their long-term stability and robustness is yet to be realized. Another area of very high efficiency solar cells based on GaAs multilayer solar cells is under intense investigation. These devices will have niche applications but because of high cost will not penetrate the large commercial market. Solar thermal systems have the unique advantage of storing the heat from solar radiation in high-temperature fluids up to values greater than 400°C for use in turbines to generate electric power. This approach presents a number of material challenges, such as long-term stability of alloys in corrosive fluids, environmentally stable reflective mirrors, and long-term stability of low-cost heat exchanger systems.[20] Some of the major disadvantages in development of large solar fields relate to their geographic location where the solar energy flux is high and the energy conversion efficiency of the system is many times greater than the current 6% to 7%. High demand for energy on Earth in regions where the average solar flux is well below 200 watts per square meter brings an additional challenge for appropriate coupling with the existing grid system and transportation of power to high demand urban regions.

Methane Hydrates: An Abundant Clean Energy

There is an abundance of methane stored as methane hydrates (clathrates) along the continental margins and permafrost regions of the Earth. Although the existence of these solids at low temperature and elevated pressure has been known for some time, it was discovered in the mid-1930s that methane hydrates crystallized as solids above 0°C in gas pipelines.[21] It is estimated that more than half of the organic carbon in the Earth's crust exists in the form of methane hydrates deposits (nearly 1×10^{16} kilograms of carbon equivalent). All the recoverable and non-recoverable fossil fuels (coal, oil, and natural gas) consist of a quarter of the carbon distribution. The remaining quarter is widely distributed amongst waste materials, peat, soil, animals, and dissolved organic matter in the oceans. The origin of these hydrate deposits is due to microbial decomposition of organic matter at appropriate temperatures and pressures. These deposits, illustrated in Figure 3,[22] dissociate back into water and methane below the sea floor due to an increase in geothermal temperature gradient and, under the proper conditions of the sediment structure, remain in large cavities.

In the Gulf of Mexico and along the Cascadia Margin and the Blake Ridge of the United States and Nankai Trough off the coast of Japan and the Andaman Sea off the coast of India, about 10^{14} cubic meters of gas are believed to be present.[23] Recent studies have uncovered vast deposits in the permafrost regions of Alaska and Canada. Technologies dealing with drilling in the continental margins, which are typically at greater depths of the water column, along with improved understanding of the physics and structure of ocean sediments, are needed to exploit this vast resource, which can either be used directly in ground transportation systems with minor modifications to the internal combustion engine, or converted to liquid by the Fischer–Tropsch process or to steam, reforming the gas to produce hydrogen.

Deep Carbon Cycle

A highly controversial hypothesis has been under debate on the subject of deep carbon reservoirs in the Earth's subsurface crust and core. A workshop on deep carbon cycle was organized by the Geophysical Laboratory of the Carnegie Foundation during 2008.[24] The hypothesis contends that large carbon and hydrogen fluxes emerge from the Earth's core to the upper strata, where they transform to form alkanes resulting from rapid drop in pressure and temperature. The debate includes issues related to the extent of deep carbon reservoirs in the Earth's core, magnitude and kinetics of carbon flux to the upper crust, and on abiotic organic synthesis. While these issues are intriguing and scientifically challenging, the origins of deep hydrocarbons remain to date unknown.

CONCLUSIONS

It is essential that, during the early part of the 21st century, humankind wean itself from addiction to fossil fuels, primarily petroleum, which has been the main source of industrial growth during the last century. A number of alternate energy production approaches, both renewable and non-renewable, such as coal, natural gas, methane from methane hydrate, biomass, fission and fusion, hydroelectric, solar, wind, ocean, thermal, and geothermal, are potential candidates that could collectively replace the need for rapidly depleting fossil fuel reserves in the Earth's crust.

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