A New Energy Regime: Possible Roles for Space Technologies and Applications

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Abstract- **Today's global energy mix is dominated by fossil fuels. However, there are clear signs indicating that our current energy regime is not sustainable. The environmental toll of fossil fuels, the related energy security issues and the inherently finite nature of fossil fuels force us to explore new energy sources and technologies. Space technologies and applications can play an important role in using our existing energy resources more efficiently, and in developing new ones. This paper develops the concept of an "energy supply chain" and gives examples of existing and future space technologies and applications that can create innovative solutions for the energy sector. Future research areas are identified and recommendations are given for establishing a more active role for space technologies and applications in the energy sector.**

I. INTRODUCTION

During the last two centuries, the phenomenal increase in energy production and consumption has been one of the major drivers of economic growth. Moving from solids, such as wood and coal, to liquids, such as petroleum, the efficiency and capability of our energy systems increased dramatically. Today, access to a steady supply of energy is widely accepted as one of the pre-requisites for economic growth and a better quality of life.

However, there are clear signs indicating that our current energy regime is not sustainable. The environmental toll of fossil fuels, the related energy security issues and the inherently finite nature of fossil fuels force us to explore new energy sources and technologies.

The main objective of this paper is to propose a framework for investigating the potential of space technologies and applications in creating a sustainable energy regime within the next two decades. This framework is based on the concept of the energy supply chain. Along the energy supply chain, space technologies and applications are considered as part of the existing and future "portfolios" of energy systems. Thus, rather than proposing a "space alone" approach, complementary roles to terrestrial energy technologies are emphasized. Therefore, energy production in space (such as solar power satellites), an activity that could be feasible in the long-term, is outside the scope of this paper.

Section II of the paper provides a brief overview of the current energy regime, while Section III examines the potential of renewable energy sources. A brief discussion of energy carriers (Section IV) is followed by the dynamics of technology – natural resources interaction (Section V). Section VI provides sample space technologies and applications that are linked to specific segments of the energy supply chain. Section VII provides recommendations for future research and concludes the paper.

II. THE CURRENT ENERGY REGIME

Today's global energy mix is dominated by fossil fuels. As of 2002, fossil fuels (coal, natural gas and oil) account for about 80% of the primary energy sources that meet the global demand for energy [1]. As Figure 1 indicates, renewables only account for 14% of the global energy mix. Biomass and waste, perhaps the oldest primary energy source, account for about 11% of the global mix, and their consumption is concentrated in developing countries. A well-established renewable energy source, hydropower, only accounts for 2% of the mix. New generation renewables, wind, solar, geothermal and others, currently account for just 1% of the global mix.

Our dependence on fossil fuels represents a typical stock-flow problem. The stock in this problem is the amount of remaining reserves that can economically be exploited. The flow is the level of production to satisfy the global demand through time.

For all practical purposes, the theoretical stock of fossil fuels is constant. All fossil fuels are formed from organic debris trapped in sedimentary rocks. These debris are transformed into fossil fuels through bacterial decay, increasing temperature and pressure over millennia [2].

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Although new reserves can be discovered and our inventory of proven reserves can be increased, the nature of fossil fuel formation generates a theoretical limit *regardless the degree of technological advances that can be achieved in the extraction and processing of fossil fuels*.

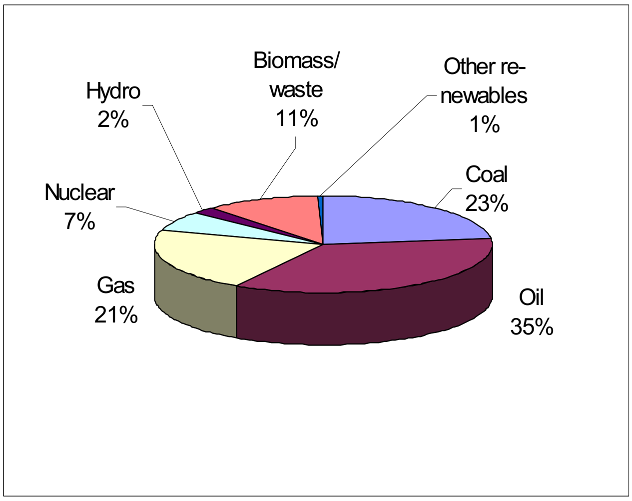

Figure 1. Global energy mix of primary energy sources as of 2002 (Source data: IEA, World Energy Outlook, 2004)

The flow in this system is nothing but constant. The worldwide demand for energy exhibits a clear, increasing trend. In recent years, the demand for energy in developing economies, especially population giants such as China and India, has surged. Coupled with the steady increase in primary energy demand from Western economies, this additional demand pressure is creating a strain on the current energy regime.

Given our current dependence on oil, the estimates for the timing of a worldwide oil production peak are causing intense debate. Such a peak will mark a milestone in the history of oil production, defining the beginning of a seller's market and increased upward pressures on oil prices. Expert estimates for the oil production peak range from 2010 to 2030 and beyond [3, 4, 5, 6].

When it comes to fossil fuels, the question is not whether or not the stocks will be depleted any time soon, but it is when fossil fuels will lose their cost advantage vis-à-vis other types of fuels. Even if the production does not peak before 2030, given the environmental and political dimensions of oil dependence, the need for alternative sources of energy is clear.

Some experts argue that prices in the energy markets do not reflect the "true" cost of fossil fuels, which includes societal costs associated with environmental and security issues. These costs include air-pollutant damage costs, damage costs from greenhouse gas emissions and oil supply insecurity costs[1][4, 5, 7, 8]. The current cost advantage of fossil fuels over renewables is likely to diminish in the next two decades since renewables have significantly lower environmental costs and they are more uniformly distributed across different nations (thereby decreasing the likelihood of resource conflicts).

III. Renewable Energy Sources

Research and development (R&D) efforts for renewable energy sources and technologies have been gaining momentum in recent years, after a period of inertia due largely to relatively low oil prices. A wide range of renewable energy sources and technologies exist, including hydro, solar, wind, and biomass.

During the past two decades, the budgets for government renewable energy R&D programs have stabilized around 600 million US$ per year[2]. Such programs are needed for increasing the performance and efficiency of existing renewable energy technologies and for discovering new ones. As it can be seen in Figure 2, these budgets are positively correlated with the price level of oil[3]. This relationship confirms a general observation about renewable energy R&D budgets: when the price levels of fossil fuels are relatively low, the incentive for creating renewable energy sources and technologies decreases.

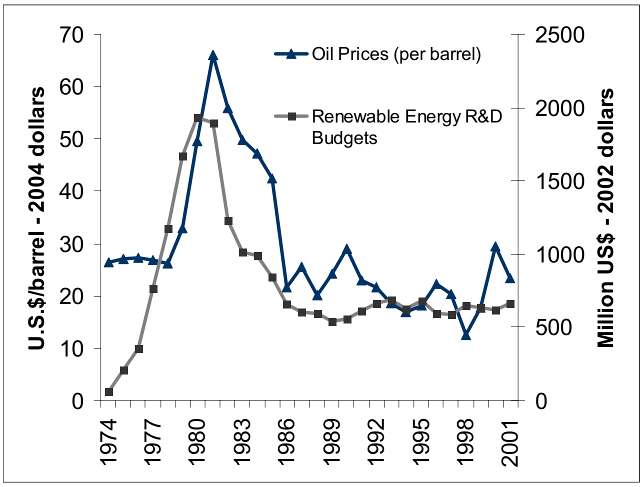

Figure 2. Oil Prices vs. Renewable Energy R&D Budgets (Source data: U.S. Department of Energy; IEA, Renewable Energy: Market and Policy Trends in IEA Countries, 2004)

The recent surge in oil prices and the slowly sinking realization that "cheap oil" may be a phenomenon of the past are likely to stimulate government and private sector energy R&D efforts. Not only the renewable energy R&D programs, but also research efforts for using fossil fuels more efficiently are likely to gain importance. This renewed interest in energy R&D can create a favorable atmosphere for promoting solutions based on space technologies and applications in the energy sector in the coming years.

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1 One example of oil supply insecurity costs is the continuing presence of the U.S. military in the Persian Gulf.

2 This figure includes the government renewable energy R&D budgets of all 24 International Energy Agency member states.

3 For the period between 1974-2001 the correlation coefficient is 0.7014.

IV. Energy Carriers

Primary energy sources have to be processed and converted into an energy carrier before they can be transmitted to the end-user [9]. Electricity is the most common energy carrier today, and it can be produced from many different types of primary energy sources.

Fossil fuels need energy careers as well. Gasoline carries the energy from petroleum; natural gas is an energy carrier by itself and can be used directly without any major conversion.

Hydrogen is seen by some experts as the next generation energy carrier. Hydrogen can carry energy from fossil fuels, renewable energy sources or by conversion from any source of electricity [9]. However, as it will be discussed in Section VI, storing hydrogen is a major technical challenge since it is much more volatile than other energy carriers. Moreover, creating a new energy transmission and distribution network is an immense infrastructure investment.

V. Dynamics of Technology – Natural Resources Interaction

Compared to the stock-flow problem of fossil fuels discussed above, renewable energy sources represent a very different system. Since most of these resources are based on natural processes that are likely to continue for a very long time (such as wind, waves and solar radiation), their theoretical stock is much higher than that of fossil fuels and furthermore, this stock is replenished regularly. However, the challenge is developing efficient ways for converting the potential energy of these resources into usable forms of energy. Technology plays a key role in this conversion.

By its very nature, technological advancement is an asymmetrical development: once a new technology is developed it does not disappear. Therefore, advances in renewable energy technologies can only go one way: towards more efficient ways and new capabilities for generating usable energy from natural processes. In other words, it is not unrealistic to assume that our future capabilities for harvesting renewable energy will be superior than our current capabilities. This overall trend is likely to decrease the significant cost advantage of fossil fuels over renewables, since renewables already have the advantage over both environmental and energy security fronts.

Figure 3 demonstrates this phenomenon. During the last two decades, the cost of electricity generation from wind and solar photovoltaic systems declined steadily. In fact, the cost of electricity generated from wind turbines (around US$ 0.05 per kWh) is now cost competitive with other means of electricity generation [5].

Solar PV technology also improved in this time period, significantly pushing down the cost of installing and operating such systems. Although solar PV electricity generation still costs at least 3-4 times as much as conventional energy sources, further improvements in the next two decades can also make it cost competitive.

As it will be discussed in Section VI, space technologies and applications can help increase the efficiency of renewable energy systems. Increased efficiency, in turn, can enable manufacturers to create new renewable energy systems which can compete with fossil fuel based systems on a cost basis.

Although the recent trend in decreasing renewable energy prices and the potential for even more progress are encouraging, most experts agree that the dominance of fossil fuels in the global energy mix is likely to continue well into the next two decades [1, 5, 10]. In order to surmount the environmental damages created by fossil fuels, researchers are working on a variety of "clean" fossil fuel technologies, such as decarbonizing fossil fuels (or carbon sequestration)[5].

One thing is clear: no single source of primary energy is going to be the answer to the booming demand for energy. Instead, we need to perceive our energy choices as part of a global energy "portfolio" and manage this portfolio by taking into account the interdependence between different energy "assets". Such a portfolio management approach can also help minimize the environmental and security concerns while ensuring an efficient use of existing resources.

Developing the concept of an "energy supply chain" is one of the first steps in this portfolio management approach.

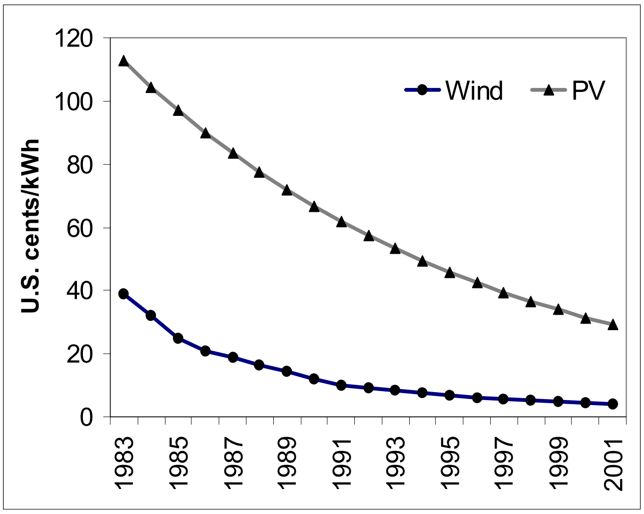

Figure 3. Trend of renewable energy prices (Source data: IEA, Renewable Energy: Market and Policy Trends in IEA Countries, 2004)

VI. Energy Supply Chain

From primary energy sources to the end users, energy is generated, stored, transmitted and distributed through the energy supply chain. For each of the major segments in the energy supply chain, space technologies and applications are already playing an important role both for renewable and non-renewable energy sources. The cases mentioned below are just some examples, and they do not constitute an exhaustive list, or inventory, of energy-related space technologies and applications.

A. Energy Production/Generation

This step involves extracting the primary energy source and converting it to usable energy. There are a variety of production methods including drilling and pumping (for oil and natural gas), mining (for coal), and turbines (hydroelectric and wind systems), among others.

(i) Oil and Gas Exploration

Oil and gas exploration companies are actively using earth observation data from both passive (e.g., optical) and active (e.g., radar) instruments. There are also plans for using hyperspectral remote sensing technologies for oil, gas and mineral exploration.

ESA's Earth Observation Market Development Programme is one example of how space applications can be used in oil and gas exploration efforts. ESA provides support to the private sector for commercializing the data obtained from various European and Canadian satellites in the form of value-added services to the oil and gas industry [11].

Currently, almost all of remote sensing satellites in orbit have either panchromatic or multispectral imagers, collecting data from a few spectral bands and with limited resolution. In contrast, hyperspectral imagers can collect data in contiguous narrow bands simultaneously (up to several hundred bands) in the electromagnetic spectrum [12]. The "Hyperion" instrument aboard NASA's EO-1 satellite provided the first set of hyperspectral data from space in 2001 [13]. It is expected that hyperspectral imagers can provide much more detailed data about the physical and chemical properties of surface features, a capability that can improve the current practices of oil and gas exploration [12, 14].

(ii) Wind Farms

Determining the optimal location for wind farms is a critical task. Satellite data can be very useful in location analysis by enabling analysts to improve their estimates of long-term wind energy yield [15]. Increasing the long-term accuracy of such estimates is also critical to manage the technical and financial risks associated with wind farm projects.

Compared to wind farms on land, offshore wind farms have much higher wind potential, but their construction and operation are generally more expensive and exposed to a higher level of technical risk. Synthetic Aperture Radar (SAR) data from earth observation satellites can be used to collect accurate information on wind speed and direction in coastal areas and provide "wind maps" [16]. For the location analysis of onshore wind farms, digital elevation models and surface roughness measurements can also be used.

(iii) Hydropower

Although globally hydropower only accounts for only 2% of primary energy sources, in water-rich countries, it constitutes a sizable portion of the energy mix. Obtaining accurate estimates of water flow around the dams is key in managing the production of hydroelectric power more efficiently. For instance, in Nordic countries, snow coverage, snow thickness, and ground temperature are the main determinants of how much power can be generated from hydroelectric systems. To this end, ESA has started a new initiative to combine optical and SAR data in order to obtain the required data even during the presence of clouds [17].

(iv) Solar Energy

Solar energy can be converted into electrical energy using photovoltaic (PV) cells. In such systems, energy from solar radiation interacts with the electrons of a semiconductor, thereby generating electric current [2].

Solar photovoltaic systems are space heritage technologies. At the beginning of the Space Race, in order to provide a steady supply of energy to satellites, both the U.S. and the Soviet Union launched research projects to develop practical solar PV technologies.

Until the 1950s, cell efficiencies were around 1%. With the advent of the Space Race and competing research programs, efficiencies quickly reached around 10% [18, 19][4]. In 1958, the U.S. Vanguard I satellite demonstrated solar PV technology as a "space first", and other satellites with PV arrays fallowed, including Sputnik-3.

Today, commercially available solar PV systems are around 21% efficiency level [20] and researchers have reached to 32.3% efficiency levels in lab environment [21]. As the efficiency levels increase, and as more efficient cell production methods are developed, the cost of energy generation from PV systems has declined steadily (Figure 3).

Although solar PV has a strong space heritage, increasing interest for terrestrial applications has generated many new R&D programs that are dedicated for terrestrial use. Laboratories in North America, Europe and Japan are actively working on new materials and processes to push the performance of solar PV systems higher.

B. *Energy Storage*

Energy storage is one of the most challenging steps in the energy supply chain and it is a differentiating factor across various types of energy networks. Although some primary energy sources can be stored efficiently, others cannot be directly stored and need a form of carrier energy.

Primary energy sources that can be stored without a conversion can be stored in a more practical way. Oil has a definite advantage in this regard, since it can be stored in liquid form at normal temperatures.

For the future development of renewable energy sources, storage remains as one of most significant challenges to overcome. One of the biggest drawbacks of wind and solar PV systems is their intermittent nature: they do not generate energy 24 hours a day, their energy output can vary drastically over the course of a single day and their output is very dependent on climate conditions. Storage technologies are critical to surmount these reliability and continuity of service issues.

Among the various storage technologies considered for renewable energy, current focus is on batteries and hydrogen conversion [5]. Space companies and agencies have significant expertise in both of these storage technologies.

For instance, as part of the U.S. Space Shuttle program, liquid hydrogen is used as fuel for rocket propulsion, and also

[4] Solar PV efficiency measures the percentage of sunlight that hits the PV cells converted into electricity.

as fuel for the fuel-cells aboard the Shuttle fleet which provide electricity and water to the crew.

Although NASA started using fuel-cells in 1960s, it took almost three decades for this technology to diffuse to other sectors, such as automotive and energy generation. Today, there are powerful research and development consortia (such as the Ford Motor Company – Ballard Power Systems alliance) that aim to bring fuel-cells as part of commercial products into the market.

Hydrogen storage know-how of the space agencies and companies can make a significant contribution to renewable energy systems. This know-how consists of building electrolizers, storage systems and operating hydrogen facilities in a safe and efficient way. Since hydrogen storage problems is seen by some skeptics as the greatest weakness of renewable energy systems, transferring this know-how to the energy sector can create immense benefits.

C. Energy Transmission and Distribution

This step in the energy supply chain involves the transmission of the energy, in carrier or primary form, from its source to centers of consumption. Various forms of transmission methods include oil and natural gas pipelines, electricity power lines, and tanker ships carrying oil and liquefied natural gas.

Much like the "last-mile problem" in telecommunications, energy distribution involves delivering the energy to the end user. Electricity grids for long-distance and urban transmission and gas stations are examples of distribution systems.

The most relevant space application for energy transmission and distribution is earth observation. EO data can be used for designing energy networks by providing geographically referenced data. Likewise, telecommunication and navigation satellites can play an important role in maintaining these networks by enabling remote monitoring of transmission nodes via satellites.

One other major area that space technologies can make a significant contribution to energy transmission is space weather. Elements of space weather, such as solar flares and coronal mass ejections, can interact with electricity transmission grids and oil pipelines and cause significant damage [22, 23]. Therefore, advances in space weather forecasting can give operators of energy transmission networks sufficient time to react and protect their networks.

D. Energy Consumption

Industrial and residential consumers are at the receiving end of the energy supply chain. Space technologies and applications can help energy utilities to forecast the energy consumption and thereby increase the efficiency of energy delivery.

Hertzfeld et al. [22] show how data from weather satellites can be used to forecast the load (demand) on energy networks both for short time horizons (2-10 days) and longer-term forecasting (1-12 months). Not only more accurate forecasts can help utilities plan their production to better serve their customers, but also it can enable more efficient transactions in the spot market where utilities trade energy.

There are many variables, such as temperature and cloud cover, which cause variations in demand for energy. Using EO and weather satellite data together, the changes in these variables, and the impact on demand can be modeled. In this way, both short-term and long-term variations in demand can be managed with more accuracy.

VII. Toward a New Energy Regime

The transition from a fossil fuel-based energy regime to a more sustainable, environmentally friendly energy system signifies a relatively new paradigm, and space applications and technologies can play an important role in this transition. As the previous section has shown, space technologies and applications are already being used to create solutions for each segment of the energy supply chain.

As the global mix of energy continues to change, and as the demand for energy increases, space technologies can applications can play an even more important role in the coming decades. However, solutions based on space assets need to be actively promoted in the energy sector. One way of achieving this is by determining the most promising space technologies and applications that can have a significant impact on the global energy portfolio.

For instance, hydrogen storage seems to be an area where the current capabilities of the space sector can be very useful for the renewable energy development efforts. This particular know-how can help increase the weight of renewable energy systems in the global energy mix. Other emerging space applications, such as hyperspectral imagers and space weather satellites can provide new capabilities to the energy sector.

The message is clear: space is already an important component of the energy sector, and many more space-based solutions are on the horizon. Seeking complementary roles for space technologies to terrestrial ones, developing innovative solutions for the energy sector by using the unique capabilities of space assets, building channels for technology transfer and actively promoting space-based solutions can significantly speed up the "buy-in" in the energy sector.

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