Energy Transitions in the Early 21st Century

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Abstract: We are in the early stages of a long and complex transition from a global economy based on fossil energy to an economy based on low carbon renewable energy. However, fossil fuel resources are abundant and widely distributed, and they will remain the dominant source of primary energy for at least the next quarter century. In the United States, displacement of coal by natural gas for electric power generation has done more to reduce CO_2 emissions than all new renewables combined, and this may occur globally for the next decade or two, even if the European Union does not take advantage of its large unconventional natural gas resources. Greater energy efficiency (not including the efficiencies associated with displacement of coal by gas) will also be more important than new renewables. Cost/benefit ratios are important for sustainability of the transition, and some energy efficiency technologies and displacement of coal by natural gas have lower cost/benefit ratios than wind power, solar power or biofuels. Money spent on the large scale deployment of wind, solar and especially biofuels would be better spent on research, development and demonstration of a broader suite of technologies that would support the energy transition, with a focus on improving the cost benefit ratios of already deployed technologies and developing alternatives. Advanced nuclear reactors, engineered geothermal systems, fossil fuel recovery coupled with CO_2 sequestration and pre-combustion or post-combustion decarbonation of fossil fuels with geological CO_2 sequestration are among the technologies that might be more cost effective than wind, solar or biofuels, and biofuels have serious adverse societal and environment consequences.

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1 Introduction

A healthy human can sustain a power output of about 1 kW (1.35 horsepower) for a few seconds and about 100 W for a few hours. Until the widespread use of fire, on the order of 100,000 years ago, this was our only source of energy, and humankind was little more than an intelligent social animal. Limited use of wind power to drive boats began about 7,500 years ago, and animals were first used for power at about the same time. Water power was first used about 2,500 years ago, and solar power has been used for passive heating for at least 2,500 years (there is a legend that Archimedes developed a concentrated solar energy system to set fire to Roman ships during the siege of Syracuse, 2,200 years ago). Two hundred years ago, the world human population had reached about one billion, the average per capita primary energy production rate was 500–750 W (less than ten times the basic metabolic rate of about 100 W), more than 90% of the primary energy was provided by biomass, and coal was starting to become an important energy source. A century later, coal provided about 70% of global primary energy production, biomass provided about 25%, oil accounted for a few percent, and hydroelectricity and natural gas were just beginning to become important. At that time, the population had grown to about 1.7 billion, and the average per capita primary energy production rate had reached about 1.1 kW.

Today, the world's population has recently passed 7 billion, the average per capita primary energy production rate has reached about 2.5 kW, and in the United States (U.S.), the average per capita primary energy consumption rate is about 11 kW[1]. Oil is now the world's largest source of primary energy (≈33% of production), followed by coal (≈27%), natural gas (≈21%), biomass and biofuels (≈10%), nuclear (≈5%[2]), hydro (≈2%) and non-bio renewables (wind, geothermal, solar, tidal, …) at 0.3–0.4%[3]. Although different sources of primary energy have risen and fallen relative to each

[1] Despite its large per capita energy consumption rate today, the per capita energy consumption in the U.S. has increased by only a factor of about 3 since 1812, less than the relative increase in many other countries. In 1812, vast hardwood forests, which covered most of the land area between the east coast and the Mississippi River, provided very large quantities of firewood for home heating and other purposes, and charcoal for industry.

[2] Based on thermal output. In 2011, nuclear power plants produced about 2500 TWh (8.5 quad) of electricity – about 11.5% of the 22,000 TWh global annual electric energy production and about 1.5% of total primary energy production.

[3] There are several ways of characterizing the relative importance of different energy sources. These include primary energy (energy at its source), final energy (the energy delivered to the end user) and monetary value. Primary energy under-weights sources such as hydroelectric wind and solar, which generate electricity directly, relative to coal and natural gas, which are used to generate electricity with an efficiency that is typically 30–60%. On the other hand, for heating applications, without a heat pump, the fraction of primary energy converted into useful heat is about the same for wind, solar, and fossil fuels. Natural gas and oil have many uses, and very little oil is used to generate electricity.

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other, all major sources have increased more or less monotonically, and the time scale on which various sources of primary energy have risen and fallen relative to each other has been on the order of a century.

The production and distribution of energy accounts for almost 10% of the global economy, essentially all other industries are highly dependent on the energy industries, and fossil fuels have transformed our way of life. There is no more effective illustration of the importance of fossil fuels than their impacts on agriculture in the U.S. At the beginning of the 20th century, 40% of the U.S. work force was employed in agriculture, and almost all the power consumed to grow food was provided by over 20 million farm animals. By the early 21st century, only 1.9% of the U.S. work force was employed in agriculture, and almost all of the power was provided by about 5 million fully mechanized, self-propelled, pieces of agricultural equipment [1]. During the 20th century, the amount of energy used for irrigation and to produce fertilizers and other agricultural chemicals also increased greatly. The reduction in the farm workforce allowed the number of people employed in manufacturing, and later in the service and technology/information industries, to grow more rapidly. Other benefits included a reduction in the amount of land under cultivation, by about 38%, and a decrease in the fraction of disposable income spent on food prepared at home from about 20% in 1900 to about 10% in 2000, while per capita calorie consumption increased and the variety and quality of the food increased owing to more effective transportation, storage and international trade. Despite these dramatic changes, agriculture accounts for only about 1.7% of U.S. primary energy consumption, which has been about 100 quadrillion Btu (quads) or about 105 exajoules in recent years. However, the amount of energy consumed by the entire food system, including transportation, storage, food preparation, etc., is almost 16 quads [2]. Today, agriculture employs 30–40% of the global workforce, down from a pre-industrial level of 70–80%. As standards of living rise and petroleum products, electricity and modern agricultural equipment become more affordable in less developed countries, agricultural employment will continue to fall.

Today, standards of living (measured by inflation adjusted per capita gross domestic product) are declining or growing very slowly in wealthy "western" countries such as the U.S., Japan and European Union (E.U.), but growing rapidly, along with per capita energy consumption, in large population "emerging market" countries such as China, India, Brazil, Russia and Indonesia. There is growing concern about the implications of providing enough energy to raise the standard of living in poorer countries with growing populations, particularly about our ability to produce enough primary energy, and the environmental impacts of doing so in a world with dwindling fossil energy resources. These concerns can be expressed in terms of the questions:

1. Can we increase the production of fossil energy, particularly oil and gas, for decades to come to improve standards of living around the world while

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we transition from fossil energy to renewable energy, even if the transition requires a century to complete?
2. Can we improve standards of living and quality of life around the world while we make a transition from fossil energy to renewable energy and maintain adequate environmental quality?
3. Are we on the best course to make a successful transition from fossil energy to renewable energy?

Acknowledging that it is impossible to predict the future, I will argue below that the answer to the first question is almost certainly yes. With much less confidence, I believe that the answer to the second question is yes, and I believe that the answer to the third question is no.

This review is concerned with the transition from a society and economy that is highly dependent on fossil energy to a system in which almost all primary energy comes from renewable sources, with a focus on the changes that have taken place during the first decade of the 21st century and the changes that are likely to take place during the "foreseeable future" – the next quarter century. Even in a "renewable energy economy", important transitions will continue as various sources of primary energy evolve and compete with each other.

2 Fossil Energy

Many recent projection of world primary energy demand during the next 20–30 years have been published [3, 4, 5, 6, for example]. While these projections differ in detail, the most credible indicate that the demand for fossil fuel liquids (oil plus gas condensate), natural gas and coal will grow during this period (but the demand for coal may peak), and the production of energy from each of these primary energy sources individually, with the possible exception of coal, will remain larger than the production of all primary energy from renewables. Based on these projections, it seems very likely that fossil fuels collectively will be the dominant source of primary energy at mid-century. However, many might question whether the expected demand can be met, based on the "peak oil," "peak gas" and "peak coal" mantras, which refer to the idea that the annual production of fossil fuels has reached or will soon reach a maximum followed by an inexorable decline on more or less the same time scale that production grew before the maximum. Very often, these mantras are wishful thinking on the part of environmentalists and those who have a vested interest in renewable energy.

In 1956, Hubbert [7] proposed that the rate of production of a natural resource in a particular area, or globally, at first grows exponentially with increasing time, but eventually reaches an inflection point at which the rate at which the production rate increases (the slope of the production rate vs. time curve) begins to decrease followed by a peak (the point at which the production rate reaches a maximum) and then a monotonic decline. Without proposing a functional

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form for the curve, Hubbert claimed that the time of peak production could be determined from the pre-peak production history if the ultimate cumulative production could be estimated. Applying this approach, he predicted that U.S. oil production would peak in 1965–1970 for ultimate cumulative production in the 150–200 billion barrels of oil (BBO) range. He also predicted that world oil production would reach a maximum in 2000, based on ultimate cumulative production of 1250 BBO, U.S. natural gas production would peak at about 14 trillion cubic feet (Tcf) per year, based on ultimate cumulative production of 850 Tcf, by about 1970 (it was 23 Tcf and still rising in 2011), and world coal production would reach a maximum in about 2150 based on an ultimate cumulative production of 2500 billion tonnes (Gt). Hubbert's 1956 paper became famous because his prediction that U.S. oil production would peak in 1965–1970 was borne out (it peaked at around the end of 1970). After the "confirmation" of Hubbert's prediction, peak oil and the "Hubbert curve" attracted a cult-like following. However, the approach used by Hubbert has important weaknesses including the sensitivity of the time at which the production rate reaches a maximum, and the maximum production rate, to the estimated ultimate cumulative production. In addition, as Hubbert was well aware, the production rate profile may differ substantially from a simple smooth curve with a single maximum. In many cases, the largest part of a natural resource is of low quality, and not economically recoverable with available technology. When new technology is developed, the estimated ultimate cumulative production may increase greatly, because the newly recoverable low grade resource can be added to the estimated ultimate cumulative production. This is exactly what has happened with oil and gas, and in the case of coal, the vast majority cannot be recovered by today's mining technology, but may be recovered in the future by means of low cost efficient underground gasification technology. Also, there is often little interest in low grade resources, and their magnitude is often greatly underestimated (this has also happened with oil and gas). In subsequent work [8], Hubbert selected the logistic function $Q(t) = Q_\infty / \{1 + \exp[w(t_{\max} - t)]\}$ for the cumulative production at time t, where Q_∞ is the ultimate cumulative production, w is the production growth constant at early times (and the production decay constant at late times), and $t_{\max}$ is the time at which the production reaches a maximum, and half of the technically recoverable resource has been produced. According to this model, the production rate is the time derivative of $Q(t)$, and it is a bell shaped curve known as the Hubbert curve. Other similar functions, such as a Gaussian (for the production rate), have been used, and the results are not very sensitive to the exact form of the function. Using a specific functional form has the advantage of more tightly constraining the predicted peak height and its position in time, and it has the very dangerous allure of predicting the time and magnitude of the production rate peak as well as the ultimate recoverable resource via curve fitting. The approach initially pioneered by Hubbert [7] is more credible, even though it lacks a precise mathematical formulation.

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During recent years, cumulative world oil production was approaching 1250 BBO (the ultimate cumulative production used by Hubbert in 1956!), and the proven reserves were of a similar magnitude. If proven reserves are assumed to be the amount of oil that will be produced in the future, the peak oil scenario can appear very convincing to some individuals. However, proven reserves greatly underestimate the amount of oil that will be produced in the future. This is illustrated by the situation in the U.S. According to a 2006 report prepared by Advanced Resources International for the U.S. Department of Energy [9], almost 200 BBO had been recovered, but an additional 400 billion barrels of recoverable oil remained. This contrasted greatly with the proven reserves of about 30 BBO at that time [10], and neither shale oil nor oil shale were included. Based on data in BP Statistical Reviews [10–15], the global crude oil proven reserves/production rate ratio increased from about 38 years in 1985 to about 46 years in 2010 (not including Canadian oil sands), and for natural gas the ratio stayed almost constant (57.9 years in 1985 and 58.6 years in 2010). During the same 25-year period, annual oil production increased by about 40%, natural gas annual production increased by about 80%, and 25 years of production was added to the cumulative productions of oil and gas. By the end of 2011, the proven reserves/annual production ratio had increased to 54.2 years for oil (including oil sands) and 62.6 years for natural gas. These behaviors are not consistent with peak oil and peak gas. Even for conventional oil and gas, new discoveries and increased recovery factors could be sufficient to allow increased production for several decades, and the amount of oil that could be produced from unconventional sources is even greater. Only the rapid growth of other *competitive* primary energy sources, a strong international commitment to curtail the production of fossil fuels, calamity or some combination of these can bring about a rapid decline in production.

2.1 Natural Gas

Among fossil fuels, natural gas has undergone the largest and most fundamental changes in recent years with the rapid growth in production from first generation unconventional sources – coalbeds, tight (very low permeability) reservoirs and shale formations. Oil and gas are formed by the thermal decomposition of solid organic material (kerogen) in fine grained sedimentary rocks commonly referred to as "shale," even though many of them do not meet the technical definition of shale. As the burial depth increases, the temperature and pressure increase and the kerogen is partially transformed into an oil rich fluid. For organic rich shales (source rocks), part of this fluid is expelled from the source rock in a process known as primary migration. If the burial depth continues to increase, the remaining organic material decomposes to form fluid that becomes increasingly gas rich as the temperature increases. The hydrocarbon fluids expelled from the source rock migrate through the subsurface under the influence of gravity (buoyancy) and the hydrodynamic forces exerted on them by flowing water/brine – very

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strongly influenced by subsurface heterogeneity (heterogeneous capillary forces and permeability). Some of the migrating hydrocarbon reaches the surface, where it is oxidized, some forms accumulations of economic interest in porous reservoir rocks, some is retained, at least temporarily in accumulations that are too small to be of economic interest along (secondary) migration pathways, and some is dispersed along migration pathways. In active petroleum systems, these processes are ongoing and hydrocarbon fluids are still moving slowly along migration pathways, entering and leaving reservoirs and reaching the surface. In many cases, large amounts of hydrocarbon remain in the extremely low permeability source rocks, and this hydrocarbon is known as shale gas or shale oil, depending on its composition.

The oil and gas industry has known about the enormous amount of hydrocarbon retained in source rocks for many decades, but it was of little interest because it was not possible to economically produce oil and gas from source rocks[4]. During the second half of the 20th century, small, but increasing, amounts of shale gas and shale oil were produced in North America (N. America), mainly by relatively small independent oil and gas companies, and the technologies needed to economically produce shale oil and shale gas in large quantities was developed and improved. The key technologies are horizontal/multilateral drilling, hydraulic fracturing and fracture propping. However, a host of other innovations have made important contributions. Only a few years ago, increased production of shale gas stimulated reassessments of shale gas resources, which indicated that they are very large, and this heightened interest in development of shale gas resources.

According to a report issued by the Energy Information Administration [16], the technically recoverable shale gas resource in 33 assessed countries amounts to 6622 Tcf, bringing the total world recoverable natural gas resource to 22,600 Tcf – almost a 200 year supply at the current production rate. Source rocks in some of the major oil and gas producing regions, including the Middle East, West Siberia, Indonesia and West Africa, were not included. It is likely that shale gas resources in these regions have not been assessed because they are of little interest when enormous conventional resources are present. In sedimentary basins, most of the rock is "shale" (mud stone, silt stone, shale, marl, etc.) with various organic contents and degrees of maturity. As the technology for recovering shale gas advances, the technically recoverable resource will increase, and even in N. America new shale gas plays will be developed. Under these circumstances, it seems reasonable to expect that the global technically recoverable shale gas resource will expand to about 25,000 Tcf, and possibly more. In terms of primary energy, this "new" gas would be equivalent to more than 4 trillion barrels of oil (TBO), or about 3.5 times all the oil produced to date, bringing the total to 41,000 Tcf, or a 350 year supply at current production rates. In addition,

[4] Knowledge of the size, shape, location and organic content of source rocks has been important in oil and gas exploration for many years.

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very large amounts of gas may be produce from second generation unconventional sources (hydrates and geopressurized brines). At this stage there is no sound basis for estimating how much gas can be recovered from these second generation unconventional natural gas resource, but gas hydrates could be the largest recoverable natural gas resource. Natural gas is now so plentiful that development of second generation unconventional gas resources could be delayed for many decades.

In the U.S., shale gas is having a very large impact on other primary energy sources. Because natural gas is now plentiful and inexpensive, and production of electricity using high efficiency combined cycle natural gas power plants generates only about 40% as much CO_2 as the old coal fired power plants that they are replacing, the urgency of increasing renewable energy generating capacity has been reduced. Only a few years ago, it was argued that the generating capacity of wind, nuclear and other renewables must be increased because the U.S. would become reliant on gas imports from countries such as Iran, Qatar and Russia, gas prices could become too high and too volatile because of imbalance between supply and demand, and gas must be transported through long distances from remote sources to meet future demand [17]. Today, with the expanding technically recoverable shale gas resources in the U.S., including large resources such as the Marcellus Shale and Utica Shale near major population centers, these arguments are much less persuasive. There is even discussion of the U.S. becoming a gas exporting country and revival of manufacturing industries because of the competitive advantage of abundant low cost natural gas. Natural gas is also becoming formidable competition for coal (because gas has a much lower environmental impact) nuclear (because of the much smaller financial risk of gas) and wind and solar (because natural gas, unlike wind, can be used for on demand and baseload power generation, and it costs less).

Because shale gas resources are widely distributed, and abundant relative to consumption rates in several high population regions (China, the Indian Subcontinent and the European Union, for example), the recent American experience is likely to be repeated around the world. First generation unconventional natural gas production is already having international impacts. For example, development of the 130 Tcf Shtockman conventional natural gas field in the S. Barents Sea has been halted because the price of natural gas in the intended N. American market has been drastically lowered by the rapid increase in shale gas production. Similarly, plans to build a natural gas pipeline from the (Alaska) "North Slope" to the lower 48 have been replaced by plans to build a pipeline to the S. Alaska coast to enable export of liquefied natural gas to Asia.

2.2 Oil

Today, light oil accounts for almost 90% of the world's total annual oil production, but about 2/3 of the remaining oil in place is heavy oil and bitumen, and the technically recoverable heavy oil and bitumen resource is about equal to the technically recoverable light oil resource. The largest oil accumulations in the world are

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located in the West Canadian Sedimentary Basin, and the Orinoco Heavy Oil Belt, Venezuela. Because of these enormous resources, the proven reserves of Venezuela are now ranked number 2, and those of Canada number 3. The discovered bitumen in the Canadian oil sands amounts to about 1,700 BBO and the total amount in place is estimated to be about 2,500 BBO. About 150 BBO can be recovered with current technology under current economic conditions [18], and this accounts for most of Canada's proven reserves. It is expected that an additional 150 BBO could ultimately be produced [18]. A quite large number of bitumen recovery technologies are being developed and used, and it is likely that the average recovery factor will be increased. Less is known about the Orinoco Belt, but it is likely that the technically recoverable resource is much larger than the proven reserves of 220 BBO. The United States Geological Survey estimate is 380–652 BBO [19].

The recovery of "shale oil" from source rocks is beginning to have an important impact in the U.S. In recent years, the Bakken-Three Forks play in the Williston Basin (North Dakota, Montana and Saskatchewan) has been a focus of attention because of the increasing production of shale oil from that resource. A recent report prepared by Bentek Energy for the North Dakota Pipeline Authority [20] suggests that oil production from the Williston Basin could increase more than fourfold from 2011 levels to 2 million barrels per day (about 10% of current U.S. consumption) by 2025. Many other N. American shale formations are known to contain hydrocarbon liquids. These include the Monterey-Santos (U.S.), Canol (Canada), Utica (U.S.), Niobrara (U.S.), Eagle Ford (U.S./Mexico), Avalon (U.S.), Barnett (U.S.), Woodford (U.S.) and Tuscaloosa (U.S.) shales. Most of these are well known shale gas producing formations, and some of them could rival the Bakken in oil production. In addition, it is very likely that other oil prolific formations will be discovered and that advances in technology will enable the currently very low recovery factors, typically a few percent, to be increased. In only ten years, the U.S. could be producing almost 4 million barrels of shale liquids per day [21]. Because of the increase in production of oil and natural gas liquids from shale, increased production of liquids from deep offshore reservoirs and other sources and increased energy efficiency, it appears that the U.S. could meet its own demand for liquid transportation fuels in ten years [21].

Much of the technology used to recover oil and gas from very low permeability rocks was developed in N. America, and large scale production also began in N. America. However, N. America occupies only 16.5% of Earth's land surface, the U.S. occupies only 6.5%, and shale is by far the most prevalent rock in sedimentary basins. Consequently, it is highly likely that most of the world's shale oil and shale gas resources are located outside of N. America, and that shale oil will "go global" in much the same way that shale gas has gone global. There are signs that this is already happening; for example, interest in the Bazhenov Shale in Western Siberia is growing rapidly. The siliceous Bazhenov shale formation is the major source rock for one of the richest petroleum provinces in the world. It extends over an

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area more than one million square kilometers in the West Siberian Sedimentary Basin, it has an average thickness of 25–30 meters, and an average total organic content of about 8 weight percent [22]. There are reports that Rosnedra, the Russian Subsurface Resources Agency, estimates that 180–360 BBO are recoverable, which would place the Bazhenov shale in the same class as the Canadian oil sands, the Orinoco Belt and much larger than Ghawar (the largest conventional oil reservoir). A rapid increase in production of liquid hydrocarbon from source rocks in sedimentary basins around the world could have important impacts on the production of oil from other oil resources such as heavy oil and bitumen that require large amounts of energy to produce and heavy oil in offshore reservoirs that must be transported to shore based facilities or distant platforms via subsea pipelines. On the other hand, innovations in heavy oil production, pipeline transport and upgrading, including down-hole upgrading, might make shale oil production less competitive.

Oil can also be produced from oil shale, kerogen rich rock which has not been buried to depths at which the temperature is sufficient to cause significant decomposition and production of low molecular weight hydrocarbons. The natural maturation process in which kerogen decomposes to form oil and gas can be accelerated by mining and heating oil shale in a retort or by heating the shale *in situ*. As is the case for most resources, high quality oil shales (those with high kerogen contents) are relatively rare. In the U.S., characterized oil shale formations contain 6–8 trillion barrels of oil equivalent (TBOE) of kerogen in place, and about 2 trillion barrels of oil (TBO) are technically recoverable. The majority of the recoverable oil (1–2 TBO) is in the Green River Shale in the Piceance (Colorado) Uinta (Utah) Washakie (Wyoming) and Green River (Wyoming) basins. The global recoverable resource is often stated to be 3 TBO. However, it does not seem to be realistic that 2/3 of the world's technically recoverable oil shale resource lies in the U.S., and it is likely that global resources are greatly understated. The oil shale resource in Israel has recently been re-evaluated from about 5 barrels of oil equivalent (BBOE) in place to about 250 BBOE in place [23], and this supports the idea that world oil shale resources may be much greater than 3 TBOE.

In the absence of a large scale modern oil shale industry, it is difficult to estimate the cost of producing oil from oil shale. Some industry estimates put production costs below $30 per barrel, but other estimates are much higher. The actual cost will depend on the location and quality of the shale, the technology used, the cost of natural gas, electricity or other sources of heat and other factors. It is very likely that large scale production of oil from oil shale would be quite profitable at today's oil prices. Oil shale will compete with other unconventional sources of oil, and expensive to produce conventional oil such as oil from deep offshore and Arctic reservoirs.

Many very large unconventional fossil fuel resources like the Green River Shale, the Bazhenov shale, the Canadian oil sands and many deep coal beds have been

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known for decades. Consequently, the cost of producing oil and gas from these sources is offset, in part, by much smaller exploration costs[5].

Further into the future, oil could be replaced with synthetic fuels. Syngas (a mixture of CO and H_2 or CO, H_2 and other gases) can be produced from natural gas, coal, biomass, petroleum coke and other carbonaceous materials, and used to make liquid fuels. At large scale, with low coal or natural gas prices, synthetic liquid fuel costs less to produce than oil from some conventional petroleum sources. Sasol has run a successful synthetic fuels business for many years [24], and synthetic fuels plants are operating in South Africa, Qatar, China and Malaysia. The ability to make synthetic fuel from a variety of carbonaceous materials, depending on price and availability is an important advantage. In South Africa, Sasol uses primarily coal, but natural gas is also used. Globally, synthetic fuel production is expected to increase, but it is not likely to play a major role during the next 25 years.

2.3 Coal

Although the proven reserves of coal have been declining for many years as a result of reevaluation, the proven reserves/production rate ratio of 112 years is larger than that of oil or gas [15]. At 861 Gt, the proven reserves are equivalent to about 3TBO or 18,000 Tcf of natural gas. Today, coal is recovered via surface and underground mining, but enormous quantities of coal have been discovered at depths too great to mine as a result of exploration for oil, gas and other resources. Summing reasonably credible estimates for very large coal resources around the world leads to a total of about 30 Tt, and the total resource could exceed 50 Tt when smaller resources and undiscovered resources are added. The main attraction of coal is its low price (the spot price of coal in the Powder River Basin, Wyoming is around $10 per tonne). However, the cost of transporting coal from the mine to the power plant or other destination is high, and it often exceeds the cost of the coal at the mine. For this reason, coal power plants are often located on or very near to coal mines.

Coal is facing serious challenges because of the well known environmental impacts of mining transportation and power generation (greenhouse gasses, oxides of sulfur and nitrogen, particulates, mercury, arsenic, selenium, lead, polyaromatic hydrocarbons, …) and the cost of mitigating these impacts. Although mitigation measures are increasing the cost of coal fired power plants, global coal production will, most likely, increase for a decade or two before it begins to decline. If it becomes economic to capture and sequester CO_2 and manage other emissions, coal could remain an important fuel far into the future.

[5] However, exploration is often conducted to find "sweet spots."

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Underground gasification could become important before mid century. A power plant which uses underground gasified coal has been in operation for about 50 years in Uzbekistan, and many demonstration projects have been conducted around the world. Oxygen or air is injected into a gasification chamber, and steam is also injected or generated *in situ*. The mixture of gases removed from the gasification chamber can be used for power generation or to produce synthetic liquid fuels. Coal gasification has several important advantages over mining and combustion or surface gasification. These include better resource utilization, lower cost, safety and much reduced environmental challenges (the ash remains in the cavity and the emission of metals, radionuclides, SO_X and particulates is greatly reduced). Another very important advantage is that large quantities of unmineable coal become a technically recoverable resource. Much of the world's coal will remain inaccessible because it consists of seams that are too thin for gasification or because it is too deep. Coal is a soft material that is easily compacted via closure of cleats (fractures) and pores, and the likelihood of cavity collapse increases with increasing depth. Nevertheless, underground gasification could very significantly increase the technically recoverable coal resource. It has been claimed that underground gasification could increase technically recoverable coal reserves in the U.S. by a factor of 3–4 [25] and that approximately 300 Gt of coal is suitable for underground coal gasification in Wyoming alone [26]. The estimated cost of producing gas via underground coal gasification is $1–2 per million Btu [26, 27] – equivalent to $1–2 per thousand cubic feet of natural gas or $6–12 per barrel of oil. Many large coal resources suitable for underground gasification are found in remote locations, and the cost of transporting the gas is very high (the volumetric heat value is only 15–30% that of natural gas). Conversion to synthetic liquid fuel and pipeline transport of the liquid is an attractive alternative, and this may accelerate growth of the synthetic fuels industry. This approach is being evaluated for the remote Perdika Basin in Central Australia, which, according to some reports, contains about one Tt of coal suitable for gasification.

3 Renewable Energy

Today biomass and hydroelectricity are the largest sources of renewable primary energy. About 10% of the world's primary energy comes from biomass, but most of this is traditional biomass (firewood, agricultural wastes, etc.), which is hard to quantify, and hydroelectricity accounts for 2–2.5%. Biofuels (ethanol and biodiesel) are approaching 1%, and all other "new renewables" are approaching 0.5%, but growing very rapidly. In the past, the most successful energy transitions, the rise of coal, followed by oil and then natural gas came about because they provided superior products at a competitive price, and governments played a relatively minor role. Governments did play a key role in large scale hydroelectric projects, but this had multiple roles including flood control and providing water for agriculture, industry and general use. Governments also played a key role in

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the development of nuclear energy, in large part because of military applications of the technology. The growth of the new renewable energy industries is driven almost solely by governments, and the industries themselves are highly dependent on government support. In 2010, the largest direct U.S. federal energy subsidies went to biofuels ($6.6 billion), wind ($5.0 billion), oil and gas combined ($2.8 billion) and nuclear ($2.5 billion) [28]. Fossil fuels, which accounted for 81.4% of the primary energy production in 2010, received $4.2 billion, while biofuels and wind, which produce far less primary energy (about 1.8% and about 0.4%), each received larger subsidies.

Instead of providing a superior product at a competitive prices, the business model for the new renewable energy industries is based on lobbying governments to require their customers to buy inferior products (fluctuating power or inferior fuels) at a high price, provide direct financial subsidies, legislate favorable tax rates not granted to competitors, provide loan guarantees and grant exemptions from environmental and other regulations based on the argument that new renewables contribute to energy security and/or are good for the environment[6]. With the likelihood that the recent increases in oil and gas production in the U.S. and Canada (a reliable source of oil for the U.S.) will continue, making the U.S. self sufficient in oil and gas or self sufficient with relatively small imports from Canada, the energy security case for massive government support for new renewable energy in the U.S. is greatly weakened, and the case now rests solely on the tradeoff between environmental benefits, if any, and the cost of supporting these industries.

3.1 Biofuels

Today, ethanol from sugarcane or corn and biodiesel, primarily from plants including palm, soy and canola, are the only significant biofuels. In 2010, the global production of ethanol was 86 billion liters (Gl) and the production of biodiesel was 19 Gl [29], compared with 30.1 billion barrels (4,785 Gl) of oil. In the U.S., approximately 40% of the corn crop is now used to produce fuel ethanol. Direct Federal Government subsidies for ethanol and a large tariff of $0.54 per gallon on ethanol imports (to protect the U.S. industry from competition with Brazil, which produces ethanol at a lower price from sugarcane) were terminated in 2012, but this has little impact since consumption mandates remained. In addition, the corn ethanol industry receives indirect subsidies via government support for corn production, and agriculture is exempt from many environmental regulations that apply to other industries. If that were not enough, Americans, and people around the world, are paying a higher price for food as a result of the corn diverted into

[6] In the United States, the wind energy industry receives a federal tax credit of $0.022 per kWh for the first ten years of operation, which amounted to approximately 12 billion dollars in 2011. Unless the tax credit is allowed to expire at the end of 2012, the cost will increase as new generating capacity is installed.

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ethanol production. Large quantities of oil and gas are used to grow corn, harvest it and convert it into ethanol – the energy return on investment is low, and the production of corn ethanol has a variety of serious environmental impacts. There is a growing recognition that large scale production of corn ethanol is becoming a self-inflicted disaster, but the U.S. government is unwilling to withdraw or modify the mandates. The importance of corn growing states in the 2012 national elections appears to have prevented the government from doing the right thing. The rapid growth of the corn ethanol industry with more than generous government, support, despite its serious problems, richly deserves the epitaph "crony capitalism." The U.S. Department of Defense has even been co-opted into the effort to drive the use of biofuels under the pretence of proving a more secure source of fuels for the U.S. armed forces[7].

There is hope that second generation biofuels such as alcohol from lignocellulosic biomaterials and third generation biofuels such as biodiesel from microalgae will provide large quantities of biofuels without some of the disadvantages of corn ethanol [30]. However, progress has been disappointingly slow, and in light of the corn ethanol experience, a full evaluation of environmental and societal impacts is needed before large scale, government subsidized, deployment. In the U.S., a cellulosic ethanol consumption mandate that cannot be met has ended up as a tax on refineries, proving that mandates cannot succeed when science and technology fail. Large quantities of lingocellulosic biomass are available, but biomass comminution, the biochemistry of converting cellulosic biomass into ethanol and the logistics of harvesting, transporting and storing biomass present serious challenges. In recent years, world production of ethanol has been growing rapidly, but growth in the production of biodiesel has been slower [29]. Given the recent experience with corn ethanol, limits on how much corn and sugarcane can be grown and the challenges that must be overcome to establish a large lignocellulosic ethanol industry, it seems likely that the rapid growth in ethanol production cannot continue.

3.2 *Wind Power*

Wind produces less than 0.5% of the world's primary energy, but about 3% of the electric energy in the U.S. In some regions, it can produce electric energy at a cost ($/kWh) that is competitive with fossil energy, but the power that it produces fluctuates with low predictability, and very often it produces little power when demand is high and much power when demand is low. Consequently, the value of wind energy is less than that produced by a baseload nuclear, coal or combined cycle gas power plants and much less than that produced by "on demand"

[7] Recently, the U.S. Navy purchased 450,000 gallons of biofuel, at a cost of about $26 per gallon, for a demonstration project.

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hydroelectric or single cycle gas power plants. Unfortunately, in most locations, the value of wind power is not known, because of the economic distortions produced by various government actions to support wind power. In addition, if utilities are forced to accept wind power, it has adverse effects on the operation of other power plants. A study conducted by Bentek Energy [31] indicates that if utilities are required to accept the fluctuating output from wind turbines, the emission of NO_X, SO_X and CO_2 may actually increase because baseload coal power plants must be operated inefficiently (with variable output), and single cycle gas turbines must be used instead of combined cycle gas turbines, which are more efficient and emit less NO_X, in order to match power supply and demand. Wind power will not become truly competitive until it can be combined with low cost energy storage. When hydroelectric power is available, and there is excess generating capacity, it can be used to match supply to demand. Large amounts of energy are already stored as the potential energy of the impounded water, and turbine startup times are short (about 1 minute). Pumped hydroelectric storage may also be used where suitable sites are available, but it is less desirable[8]. For diurnal applications, all other technologies are at least twice as expensive as pumped hydroelectric storage. Pumped hydroelectric, underground pumped hydroelectric, underground compressed air and underground heat storage could be practical for longer time scales. However, costs increases as the storage capacity increases, the efficiency of underground compressed air energy storage is less than the efficiency of pumped hydroelectric energy storage, and the efficiency of underground heat storage (of electric energy with power regeneration) is much smaller. Today, the pumped hydroelectric storage capacity far exceeds the capacity of all other bulk energy storage systems. After decades of research development and demonstration (RD&D), batteries are not competitive for large scale energy storage, but flow batteries (rechargeable fuel cells) may become competitive.

There is interest in offshore wind because it is, on average, more powerful, there is less miss-match between the diurnal power variation and demand, the capacity factor is higher, and wind turbines may be out of sight. However, the costs of the supporting structure, installation and maintenance are high. The economics of a 5 MW offshore wind turbine that produces less than a million dollars worth of electricity per year is very different from the economics of an oil platform that produces a billion dollars worth of oil per year. Offshore wind power could be prohibitively expensive, and absent technology breakthroughs, rapid growth in capacity could stop at an insignificant level. Survivability under extreme weather conditions is also an important concern.

[8] Underground pumped storage could alleviate the site restrictions, and it would reduce the environmental impacts. However, the cost of this technology is quite uncertain.

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3.3 Solar Power

Like wind power, solar power fluctuates, but the seasonal and diurnal components are predictable, and the fluctuations in solar power partially complement the fluctuations in wind power (on average, the wind turbine power output is highest at night). Solar voltaic energy is more expensive than fossil, nuclear, and wind energy, and solar thermal is even more expensive. However, solar thermal power plants are being installed with enough heat storage capacity to mitigate diurnal variations in power output. A variety of off-grid solar power applications have very high values in use, and in these applications solar power is competitive without government intervention. Because of government intervention, grid-connected solar power capacity will grow rapidly during the next few years. However, it is unlikely that solar power will become a significant fraction of total global power generation during the next 20 years.

3.4 Geothermal Energy

The contribution of conventional geothermal energy to the world's electric generating capacity is negligible, but the heat flux through Earth's continental land surface is about 9,000 GW. Unfortunately, the heat flux density (about 60 mWm^{-2}) is much too small to be useful, but, at least in principle, large quantities of heat could be mined from the upper part of Earth's crust by generating fractures between one or more injection wells and a production well using technology similar to that used to recover oil and gas from very low permeability shales, and pumping a heat transport fluid (probably water, but possibly supercritical CO_2) through the fractured rock and into the production well. The hot fluid emerging from the production well would then be used to drive a turbine and generate electricity. Typically, the geothermal gradient (the rate at which the temperature increases with increasing depth) is about 25 k per kilometer, but it is significantly greater over wide areas, which would be the first targets for this engineered geothermal system (EGS) technology. The environmental impacts of engineered geothermal systems are expected to be very low, in part because of its small footprint relative to other renewable energy technologies. The main challenges are economic – the cost of drilling, fracturing and fracture propping (if necessary) relative to the value of the power produced and the economics of power generation from a relative low temperature source[9]. However, many detailed technical issues related mainly to the geochemistry and geophysics of the reservoir would determine how much power could be produced and for how long. A deeper reservoir would produce hotter fluids, which would increase the amount of heat that could be extracted and

[9] Geothermal turbines are large relative to turbines of the same capacity working with a higher temperature heat source. Stress corrosion cracking is an important issue, but very good high temperature mechanical properties are not required.

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the energy efficiency, but the drilling cost would be higher, and the lifetime of the system would probably be shorter. The development of EGS technology receives little support relative to the support for wind, solar and biofuels, but, if successful, EGS would produce baseload power (not the fluctuating power produced by most other renewable power sources).

4 Nuclear Energy

About 5% of the world's primary energy is produced by nuclear fission reactors. This is a very low emissions technology, with most of the emissions coming from uranium mining, fuel processing, power plant construction and production and fabrication of the materials used in the power plant. The fraction of the energy in the fuel that is used (the burnup) is only a few percent, and if the amount of energy produced from the fuel could be increased, by increasing the burnup in today's "once through" reactors, uranium would be more valuable, and lower grade ores could be used. If a full nuclear fuel cycle is used in the future, it would probably be practical to extract uranium from sea water, which would make nuclear fission energy essentially renewable. The most often discussed challenges for nuclear energy are nuclear accidents, nuclear proliferation, terrorism and nuclear waste management. Only the Chernobyl accident caused a large number of deaths, and the number of deaths and injuries from underground coal mining far exceeds those caused by nuclear power production. Nuclear proliferation, and the possibility that terrorists might gain access to nuclear materials are serious issues, but the international community has been unable to prevent "rogue" nations who want nuclear weapons from obtaining them, and these nations are the most likely source of nuclear materials for terrorists. If necessary, high level nuclear waste can be safely stored for centuries in dry form in casks. The best thing to do with these casks is to place them in geological repositories such as Yucca Mountain, and keep them accessible for inspection and possible future use.

Today, the most important challenge for nuclear power in the U.S. is financial risk. Nuclear power plants have become so expensive, largely because of safety and security related costs, that it takes decades from the time that construction begins before they become profitable[10]. Nuclear power plants have very long lives, and they are very profitable once they have been paid for. However, if a reactor must be permanently taken out of service during the decades before it becomes

[10] A recently started $14 billion project will add two 1.1 GW reactors to the Vogtle nuclear power plant, Georgia, U.S. A naive estimate based on the cost of the project, a 90% capacity factor, the average wholesale price of electricity in the U.S. and the average cost of operating and maintaining nuclear power plants suggests that it will be 2043 before the project begins to make a profit. Of course, it is likely that the utilities that own the reactors will charge a higher price for the electricity. However, a cost overrun of almost one billion dollars has already been reported, just a few months after the project started.

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profitable, the operator will take a large loss. In addition, the basic technology is decades old during most of the operating life of the reactor[11]. In contrast, natural gas power plants cost much less, they can be constructed rapidly, and if the price of gas is low, they quickly become profitable. Small factory built reactors (small modular reactors) may reduce the cost and financial risk since they would allow increased demand to be met incrementally, and production of many identical reactors in a factory should cost less per kW than on-site construction.

Nuclear power appears to be entering a period of relative decline in western countries[12]. However, in countries like China and India, which have a greater need for energy, nuclear generating capacity will, most likely, grow significantly during coming decades. The development and deployment of safer simpler and cheaper nuclear reactors could dramatically improve the fortunes of the nuclear industry[13]. Several types of high temperature gas cooled reactor could achieve these goals. The high outlet temperature of this type of reactor would increase the efficiency of power generation and allow nuclear reactors to be used in large scale industrial applications such as synthetic fuel production, and in the recovery of unconventional fossil fuels. The TRISO fuels used with this type of reactor would enable higher burnup, and this, as well as the higher efficiency of converting heat to power, would reduce fuel and operating costs.

5 Energy Efficiency

Some energy systems such as electric motors, electric generators and fuel cells are very efficient, and it will be difficult to achieve large additional gains. Heat engines such as thermal power plants are limited by their Carnot efficiencies, but some of them operate well below this limit. Driven by financial incentives, the efficiency of thermal power plants has been increasing for many years. Additional gains can be expected, but in the absence of radically new technology, large gains are not likely. There are, however, opportunities for large gains in other directions including vehicles, insulation and the use of advanced heat pumps for heating and air conditioning. In addition, many old power plants and other old energy systems

[11] The Fukushima reactors were installed more than 40 years ago, and it is likely that more modern reactors would have fared better during the Fukushima nuclear accident following the March 11, 2011 magnitude 9.0 Tohoku earthquake and tsunami.

[12] Francois Hollande, the recently elected President of France, has stated that he wants to reduce France's reliance on nuclear energy from about 75% to 50%, Italy has abandoned plans to increase nuclear power production, Germany plans to shut down all of its reactors by 2022 and reduction in nuclear capacity is very likely in Japan. About 2 years ago, the United Kingdom was planning to build up to 16 new reactors, but now it is uncertain what will happen.

[13] Simplicity is not essential, but it is a key enabler of greater safety and lower cost.

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will be replaced by more efficient new systems, even if significant additional technological advances do not occur.

There are many ways in which the efficiency of vehicles can be improved, including greater engine efficiency and the use of light high strength composite materials. If the mass of the engine, particularly the mass of its moving parts, can be reduced, the mass of other parts of the vehicle can be reduced leading to a significant overall weight saving and increase in efficiency. However, the greatest gains could come from electrification based on rechargeable batteries or fuel cells. Hybrid electric vehicles use a battery driven electric motor in conjunction with an internal combustion engine to drive the vehicle. By recharging the battery when power demand is low and using the electric motor to augment the internal combustion engine when demand is high, the internal combustion engine can be operated at near-peak efficiency most of the time. In addition, regenerative braking uses the kinetic energy of the vehicle to charge the battery during braking. Plug-in hybrids have a much larger battery, which can be charged from an external power source. At this stage, plug-in hybrids have little to offer. The large batteries are very expensive, and add considerable mass to the vehicle. The CO_2 emission from the Chevy Volt is essentially the same whether it is powered by the gasoline engine or the battery for the recent mix of power plants in the U.S., and the vehicle would emit less CO_2 if it used the gasoline engine alone (or a smaller gasoline engine) and did not carry the battery. The main advantage of plug-in hybrids is that they transfer air pollution from densely populated areas to more lightly populated areas where power plants are located. Standard hybrid electric vehicles, on the other hand, have a much smaller cost penalty, a larger reduction in CO_2 emission, and less concern about having to replace a very expensive battery. The sales of both standard hybrid and plug-in hybrid vehicles are expected to grow rapidly during the next 25 years, but plug in hybrids will lag far behind standard hybrids. Considering the relatively small current global sales of hybrid vehicles (almost one million vehicles in 2011 vs. a total of about 73 million light vehicles) and the 16–18 year lifetime expected for vehicles sold today, most vehicles on the roads 20 years into the future will still be powered by internal combustion engines alone.

6 Environmental and Societal Impacts

All types of energy production have a multitude of impacts on the environment and on society, and a balance must be struck between the essential role that large scale energy production plays in our civilization and its negative impacts. Unfortunately, there is no consistent way of quantifying the consequences of energy production across all energy industries, and if there was, the results would differ for different countries and regions. How can air pollution by a coal power plant be quantitatively compared with 60–80 golden eagles killed each year by wind turbines in the Altamont Pass area, California, with fear (rational and irrational) of nuclear

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accidents or hydraulic fracturing or with increased eutrophication in the Gulf of Mexico caused by corn ethanol production? With the exception of greenhouse gas emissions, most environmental problems can be managed – at a cost. However, for coal and biofuels, the cost may be too high.

In recent years, water withdrawal for fossil energy production has become a contentious issue and irrational fear has been roused by non-governmental organizations[14] (NGOs). Water is not consumed, but withdrawal of water for one application reduces its availability for other applications and/or degrades its quality. Water is used to produce oil, but less than 5 volumes of water are required to produce 1 volume of oil, including oil from oil sands and oil shale, so one gallon of water is used to produce oil worth 50 cents or more. Using 5 million gallons of water for multistage hydraulic fracturing of a single gas well may seem like a lot, but, on average, 20 average suburban American families consume this much water every year, and one gallon of water is used to produce well over one dollars-worth of gas, even at the very low recent gas prices in N. America. The use of water for hydraulic fracturing is very small compared with the amount used for agriculture and other uses, and its value in use is much higher. Even in most arid areas, there is sufficient water for hydraulic fracturing with only a small impact on other uses, except under severe drought conditions. On average, more water is used to produce a gallon of ethanol from corn than is used to produce a gallon of gasoline, and the gallon of ethanol has only about 2/3 of the combustion energy. If irrigation is required to grow corn, and this is becoming more common as ethanol mandates require increased corn acreage, the value of the fuel produced by one gallon of water is on the order of $0.01.

Environmental NGOs have also played up induced seismicity and water contamination. However, credible studies indicate that the risks associated with induced seismicity and the migration of the fluids used for hydraulic fracturing from the hydrocarbon bearing rocks to freshwater aquifers or surface waters are small [33, 34]. Estimates of the number of hydraulic fracturing treatments conducted to date vary substantially, but it exceeds one million[15], and there have been very few, if any, instances in which it has been established that ground water

[14] The publicity about water withdrawal for fossil fuel recovery has become so extreme that concern has even been expresses about taking water for the Mackenzie River for development of the Canol shale resource [32]. The Mackenzie River is the second largest in N. America, it has an average discharge of 10,000 cubic meters per second, and most of the catchment lies upstream of the Fort Good Hope area in which the shale is located. Only 1% of the water flowing annually in the Mackenzie River near Fort Good Hope would be sufficient for about 80,000 multistage "frac jobs" requiring 20,000 m^3 (5.3 million gallons) each, and there are virtually no other withdrawals! For comparison, about 1,000 frac jobs will be conducted to produce oil from the Bakken shale this year.

[15] However, many of these hydraulic stimulations were been carried out on a relatively small scale to stimulate low productivity oil wells.

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contamination was caused by hydraulic fracturing at normal depths. Inadequate well casing and failure to properly manage flowback/produced water are the most likely pathways for water pollution [34]. These, problems are common to essentially all oil and gas recovery technologies, not just those that involve hydraulic fracturing, and they are manageable.

Climate change associated with energy related greenhouse gas emissions (CO_2, CH_4, N_2O, SF_6, refrigerants) is by far the most serious environmental challenge. There is no doubt that injecting gases with infrared absorptions (and emissions) changes the transportation of radiation in the atmosphere, and that if the amounts are large enough and the infrared spectra include absorptions that are not already saturated by other gases (or the same gas), significant climatic changes will occur. However, because of the complex, sometimes poorly understood, coupling between relevant processes in the atmosphere, hydrosphere, biosphere and geosphere, it is extremely difficult to predict global and local climate changes. In addition, the need to represent subgrid scale processes and heterogeneities by coarse grained sub-models in the numerical models for climate change adds to the uncertainty. There are also large uncertainties associated with the impacts, both positive and negative, of climate change, and the economic and societal impacts of the measures that must be taken to reduce the emission of greenhouse gases. The pace at which low greenhouse gas energy technologies will be deployed and the path that will be followed will depend, in part, on the credibility of climate science and environmental science communities with the broader scientific community and with the public at large, climate science politics and the outcomes and credibilities of economic studies. Economic and environmental studies depend on models, assumptions, and often selection of the boundaries of the models, and they cannot be rigorously validated. These circumstances make predictions very uncertain and susceptible to biases (both intentional and unintentional).

Greenhouse gas induced climate change is a global problem, but it is not likely that a global solution will be found. For any country, the emission of greenhouse gases by others is more important than their own, and some countries will benefit from climate change, providing it is not too large. In addition, the costs of reducing greenhouse gas emissions will vary greatly among countries and regions, depending on their current sources of energy and the nature of their economies. Under any circumstances, the cost of reducing greenhouse emissions is important, and measures that have a low cost/benefit ratio will be the most sustainable. According to one study [35] nuclear power (replacing combined cycle natural gas or coal), combined heat and power and insulation, on average, reduce costs, while biofuels have the highest CO_2 abatement costs among technologies already deployed on a significant scale. Reduction of coal consumption via biomass/coal fuels was also found to be among the most expensive technologies. Of course, the uncertainties are large, and the study found that both wind and more efficient coal fired power plants can also have a negative CO_2 abatement costs under some circumstances. This 2006 European investigation did not include all technologies, and the results

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would be different for other regions and other times. In particular, displacement of coal by natural gas, which is occurring without government support in the U.S., is very cost effective where natural gas is abundant and inexpensive[16].

Carbon dioxide enhanced oil recovery (EOR) has produced more than one BBO in the Permean Basin, Texas using CO_2 from natural sources. If CO_2 from power plants was used instead, this would be a practical and cost effective way of storing it. According to a study conducted by Advanced Resources International [36], it might be possible to increase the U.S. recoverable oil resource by about 100 BBO using next generation CO_2 EOR, and the amount of CO_2 stored could be almost as large as the amount of CO_2 emitted when the oil is burned. Additional advances in CO_2 EOR might make oil recovered via EOR carbon neutral, even including the CO_2 emitted during oil production. It might also be possible to enhance the production of natural gas and store CO_2 by injecting it into unmineable coalbeds or hydrocarbon bearing shales, since CO_2 is more strongly absorbed by carbonaceous materials and more strongly adsorbed on mineral surfaces than methane. However, development of OER technologies for shale gas and shale oil is still at a very early stage.

Low cost CO_2 capture from power plant effluent is the key to economically competitive carbon capture and sequestration, and the widespread application of CO_2 EOR. The cost of CO_2 capture decreases and the CO_2 recovery factor increases as the CO_2 concentration in the effluent increases, and both chemical looping combustion and oxyfuel technology (combustion in a recirculating mixture of O_2 and CO_2) produce effluent with high CO_2 concentrations. The gasification of high carbon fuels produces a mixture of gases that can be reformed to produce a gas that consists primarily of CO_2 and H_2 or CO_2, H_2 and N_2, and the high concentration CO_2 can be removed before combustion. This could become an economic technology for low carbon power generation, production of CO_2 for EOR and production of H_2.

The U.S. CO_2 emission decreased by 9.1% between 2007 (the peak year) and 2011, and based on data for the first 5 months of 2012, the reduction in 2012 will be greater than in any other year. This reduction has multiple causes, including poor economic performance. However, displacement of coal by natural gas is the primary cause. Meanwhile, in the European Union (E.U.), which is also suffering from poor economic performance, but has chosen not to develop its large shale gas resources, CO_2 emissions are expected to increase by about 3% in 2012 because natural gas is expensive in the E.U., and more coal will be used to generate electricity. The reduction in nuclear power generation in Germany is also contributing to increased electric power production from coal.

Faced with the high cost of renewable energy subsidies and associated costs such as upgrading electric grids, debt ridden E.U. countries are cutting back their renewable energy subsidies and reassessing their energy policies, and if Japan decides to

[16] However, regional cooling caused by particulate emission from coal power plants should not be overlooked.

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give up its nuclear reactors, it will not reach its goal of cutting CO_2 emission by 25% from 1990 – 2020. This illustrates the importance of cost/benefit ratios in the attempt to reduce greenhouse gas emissions. Poorer countries are expecting financial and technological assistance if they are to reduce their CO_2 emissions (or reduce the rate at which they are increasing). Given the dismal economic conditions in the U.S., Japan, and Europe, which would be exacerbated by higher energy costs, access to cost effective energy technologies may be the only useful assistance that they can provide.

7 Conclusions and Discussion

There may be good reasons to accelerate the inevitable transition from an energy system based on fossil fuels to a renewable energy system, but peak oil, peak gas and peak coal are not among them. In addition, the renewable energy industries have not, so far, been very successful at increasing energy security, reducing environmental impacts or providing low cost energy. In fact, in the U.S., the growth of power generation by natural gas at the expense of coal has done more to improve environmental quality and reduce CO_2 emission than new renewable energy, and many other countries will soon benefit from this transition.

First generation biofuels were "sold" to the citizens of western countries as "green fuels" or "clean fuels" that would reduce dependence on imported oil, improve environmental quality by reducing greenhouse gas emissions, contribute positively to rural economics and society and provide fuel at a cost lower than that of fossil fuels. When the U.S. Energy Policy Act of 2005 and the 2003 E.U. Renewable Energy Directive, which drove a multitude of government interventions in support of biofuels, were enacted, a large increase in first generation biofuels production was supported by a broad coalition of agribusinesses, environmental NGOs, government departments and other organizations. For example, in the U.S., the Natural Resources Defense Council (NRDC) supported the Energy Policy Act of 2005 [37] based, in large part, on the idea that establishment of a corn ethanol industry would build the infrastructure needed for a cellulosic ethanol industry [38], despite the fact that no credible technology for commercial cellulosic ethanol production existed at that time (and cost competitive cellulosic ethanol production is still more a dream than a reality today). The U.S. Environmental Protection Agency and the Departments of Agriculture and Energy also supported development of the fuel ethanol industry [39, 40], and in 2008, there was still broad public support for increased use of ethanol, including support from "environmentalists" [41]. However, the benefits claimed for first generation biofuels have turned out to be non-existent[17] or greatly exaggerated,

[17] For example, in some cases, increased first generation biofuels production has, very likely, increased atmospheric CO_2 levels for decades to come because of land use changes that release carbon to the atmosphere and incur a "CO_2 debt" that will require many decades or even centuries to pay off.

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the future of second and third generation biofuels are in doubt, and the cost has been enormous. The U.S. federal tax credits for corn ethanol have cost $45 billion, and the increased fuel and food costs associated with ethanol consumption mandates continue to accumulate. According to Friends of the Earth, meeting the EU Renewable Energy Directive that 10% of all energy used in transportation must come from renewable sources by 2020, which will be met almost entirely by first generation biofuels, will cost EU taxpayers and consumers € 94–126 billion ($120–165 billion), without reducing greenhouse gas emissions [42]. When the costs in other countries are added, the total cost of government actions in support of first generation biofuels in western counties is likely to exceed a quarter of a trillion dollars by 2020. We are now faced with the politically difficult challenge of letting biofuels industries that should never have existed die from withdrawal of massive government support.

Hopefully lessons can be learned from the biofuels experience, and the benefits of developing future renewable energy technology industries will be higher than their costs. Other very costly government actions in support of large scale deployment of new energy technologies should be scrutinized, and there should be a renewed focus on RD&D, which costs much less than deployment. However, the forces that drove ill conceived biofuels legislation, including political and economic self-interest, ideology and compulsion to do something about a perceived problem without evaluating the costs and benefits, are as strong today as they were in the past. The U.S. Energy Policy Act of 2005, the 2003 EU Renewable Energy Directive and a similar legislation was enacted during a time of prosperity, and it will be much more difficult to justify spending hundreds of billions of dollars to support new energy technologies during the ongoing period of massive national and state budget deficits and austerity. It is sobering to consider the benefits that might have accrued if a quarter of a trillion dollars had been spent to support RD&D on a broad range of energy technologies between 2005 and 2020. By now, the “green fuels” and “clean fuels” of a decade ago have become “black fuels” and “dirty fuels” in the eyes of environmental NGOs, including many of those that initially supported first generation biofuels, and public support is waning. However, great damage has been done, and important opportunities have been lost.

The allure of “green jobs” may be compelling in times of high unemployment and underemployment, but the revival of the nuclear energy industry and increased oil and gas production would also create new jobs. In the end, the cost of energy may have a much larger impact on employment than the number of new green jobs or fossil energy jobs. Going back to an economy in which 40% of the workforce is employed by farming would also create many new jobs, but few of us would consider that to be progress. We are probably better off if as few of us as possible produce the basic necessities of life, including energy. This has certainly been the trend in modern society as we have progressed from agriculture

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to manufacturing to services (including high end services such as health and education) and information.

Instead of spending large amounts of money on the deployment of pre-competitive and non-competitive renewable energy technologies, we would be better of by removing barriers to the deployment of competitive technologies that can reduce greenhouse gas emissions and improve environmental quality. We should also focus more strongly on the RD&D needed to make pre-competitive renewable technologies competitive, and on developing a broader suite of energy efficiency technologies and low carbon energy technologies, including advanced nuclear reactors, engineered geothermal systems, CO_2 EOR, and pre-combustion and post-combustion fossil fuel decarbonation with carbon sequestration. Other technologies that are further from large scale deployment, such as wave power, production of synthetic fuels from CO_2, hydrogen production and storage[18] and nuclear fusion, should also be pursued more vigorously.

Most government interventions in support of renewable energy deployment reward production volume over cost reducing innovation, and the most important threat to rapid growth of the renewable energy industries is curtailment of government largesse. Unless more emphasis is placed on RD&D focused on reducing costs and developing new economically competitive technologies, and wind power, solar power and bioenergy are exposed to more competition from other energy technologies, the transformation from fossil energy to renewable energy will be much more expensive than necessary. In particular, "renewable fuel standards" and "renewable portfolio standards" (euphemisms for consumption mandates) that virtually guarantee the success of specific energy technologies, irrespective of competiveness and innovation, and other legislation that virtually guarantees financial success irrespective of cost and performance, reduces the pace of innovation. As a result of current renewable energy policies, we are likely to find that in 10–20 years' time we are burdened with large uncompetitive biofuels, wind power and solar power industries that we can no longer afford to support, and this may well lengthen the transition from fossil to renewable energy.

The argument that we must immediately build up energy industries that are not yet competitive is not convincing. The relatively small Norwegian energy company Statoil[19] has become a leader in offshore oil and gas technology, despite being late to the game. Production of offshore oil and gas requires command of a much larger suite of advanced technologies than manufacturing and deploying wind turbines.

[18] Hydrogen is an important energy material. It is used in large quantities to upgrade and refine fossil fuels. In the future, it could be used for large scale energy storage (via chemical looping and fuel cells), the production of synthetic fuels and as a carbon free fuel.

[19] Statoil has 21,000 permanent employees vs. 101,000 for Shell, 84,000 for ExxonMobil and 80,000 for Petrobras.

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