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Article

Fossil fuels and clean, plentiful energy in the 21st century: The example of coal

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ABSTRACT

Many people believe we must quickly wean ourselves from fossil fuels to save the planet from environmental catastrophe, wars and economic collapse. However, we have the technological capability to use fossil fuels without emitting climate-threatening greenhouse gases or other pollutants. The natural transition from conventional oil and gas to unconventional oil, unconventional gas and coal for producing electricity, hydrogen and cleaner-burning fuels will decrease energy dependence on politically unstable regions. In addition, our vast fossil fuel resources, perhaps especially coal, are likely to remain among the cheapest sources of clean energy for the next century and perhaps longer, which is critical for the economic and social development of the world's poorer countries. By buying time for increasing energy efficiency, developing renewable energy technologies and making nuclear power more attractive, fossil fuels will play a key role in humanity's quest for a sustainable energy system.

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Fossil fuels and clean, plentiful energy in the 21st century: the example of coal

1. Introduction

Many people believe we must quickly wean ourselves from fossil fuels – oil, natural gas, and coal – to save the planet from environmental catastrophe, wars and economic collapse. In this paper, I argue that this view is misguided. I present, instead, evidence to support the hypothesis that fossil fuels can play an integral part of an energy system that can be characterised as sustainable.¹

For one thing, we have the technological capability to use fossil fuels without emitting climate-threatening greenhouse gases or other pollutants. Also, while we may be reaching limitations in the search for conventional oil and natural gas, the resulting market-driven transition from conventional oil and gas to unconventional oil, unconventional gas and coal for producing electricity, hydrogen, and cleaner-burning fuels will decrease energy dependence on politically unstable regions.

In this paper, I elaborate on this hypothesis by focusing especially on the prospects for coal, the most widely dispersed and easily accessible of the fossil fuel resources. In Section 2, I present a definition of energy system sustainability. In Section 3, I show why our current energy system is not sustainable. In Section 4, I explain how fossil fuels, in particular coal, can meet our energy needs without significant environmental harm. In the interests of brevity, I focus on greenhouse gas emissions from the use of coal to produce clean forms of secondary energy, namely electricity and hydrogen. I also provide rough cost estimates. This is the largest section of the paper. In Section 5, I present a multi-criteria approach to compare a fossil fuel like coal to its energy supply competitors: renewable energy and nuclear power. In section 6, I discuss the policy implications and present the conclusions.

2. Defining energy system sustainability

I apply a simple definition of energy system sustainability. To be sustainable, an energy system must meet two conditions.

- First, the energy system must have good prospects for enduring indefinitely in terms of the type and level of energy services it provides. Moreover, given the significant energy use that will be required to improve human well-being in much of the developing world, the size of the global energy system would ideally grow substantially over this century. A sustainable global energy system must be able to provide this expanded level of energy services indefinitely.
- Second, extraction, transformation, transport, and consumption of energy must be benign to people and ecosystems. Flows of the energy system's material and energy by-products must correspond with the ability of land, air, and water to absorb and recycle them without significant negative disruption. In this sense, both the known, cumulative impacts of the energy system must be negligible and any extraordinary risks it poses must be extremely unlikely – and ones from which the system could recover within a reasonable period of time, perhaps aided by rehabilitation efforts. In sum, a sustainable global energy system must have low impacts and low risks.

¹ What I present here is a short version of the more detailed arguments and evidence in my recent book *Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy* (2006).



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Both of these conditions are inherent in most working definitions of sustainability. If the system cannot endure, perhaps because some irreplaceable input is exhausted, it cannot be sustainable. If the system is ultimately toxic to humans and the environment, then it also will not endure, this time not because of resource exhaustion but because of disruption and destruction of natural systems and harm to humans.

It is commonly assumed that the way we consume the earth's fossil fuels must certainly be unsustainable.

It is commonly assumed that the way we consume the earth's fossil fuels must certainly be unsustainable given that fossil fuels are a rich and irreplaceable endowment produced from millennia of biological and geological processes. Consumption of them today leaves nothing for the future, and the alternatives will be difficult to develop and much more expensive. This seems like a safe assumption. But is it?

3. The global energy mix: what is it and where is it headed?

To determine if our energy system is sustainable, we need to estimate where it is headed. I reviewed several forecasts of the long-term evolution of the global energy system and from these selected two mainstream scenarios to guide my 'current-trends estimate'. The scenarios I used are from the 1992 Intergovernmental Panel on Climate Change (scenario IS92a) – as reported in Leggett *et al.* (1992) – and the 2001 World Energy Assessment (scenario B) – as reported in Goldemberg and Johansson (2004). Both of these scenarios share many assumptions, but they also differ in certain respects. Both assume similar trends for income growth: a global level of gross world product rising from \$32 trillion in 2000 to above \$200 trillion (in 2000 prices) in 2100. Both assume similar trends for energy use: rising from 430 exajoules (EJ) to about 1,500 EJ in 2100. Both assume a global population above 11 billion in 2100. They both show a stagnation of large hydropower as land use conflicts intensify, a decline in conventional oil as its supplies are exhausted, and a healthy growth rate for biomass (for electricity generation and production of biofuels) and other renewables such as solar, wind, and small hydro. In meeting the huge increase in energy demand, however, scenario B relies on a dramatic expansion of nuclear and natural gas while the scenario IS92a suggests that coal will be more dominant. My scenario takes a median position between these contrasting views.

Relative to the two scenarios discussed above, I project a somewhat lower population in 2100 of 10.5 billion, a value recently suggested by the United Nations and other population forecasters. My current-trends projection has global economic output increase (in constant prices) from \$32 trillion in 2000 to \$80 trillion in 2050 and \$230 trillion in 2100. This implies an average global economic growth rate of 2 percent per year, similar to the average growth rates of recent decades, and results in global economic output that is seven times the current level. Dividing global world product by the smaller population in my current trends means that average income (GDP/POP) grows from about \$5,000 per capita in 2000 to \$8,500 and \$22,000 in 2050 and 2100.² The average income of \$22,000 is comparable to current levels in industrialised countries. This is a global average; I make no specific assumption about the relative incomes between developing and industrialised countries other than to include some narrowing of the disparity in my estimated energy uses in different parts of the world.

I assume that global primary energy intensity (E/GDP) will continue the downward trend of the past five decades, although its rate of decline will be slower in the first half of the century as developing

² I call global economic output 'GDP', although a more accurate term is global world product.

countries expand their more energy-intensive sectors, and then more rapid as these countries adopt more sophisticated technologies and shift to a greater role for the services sector. Primary energy intensity falls from 13.6 (megajoules) MJ per dollar of gross world product in 2000 to 9.6 in 2050 and 6 in 2100. This represents an annual rate of decrease of 0.69 percent from 2000 to 2050 and 0.93 percent from 2050 to 2100. The 0.93 percent is close to the rate of decrease that occurred during the 15 years following the oil price shocks of the late 1970s and early 1980s.

As in the past, increases in population and especially economic output swamp declines in energy intensity so that total primary energy use grows from 429 EJ in 2000 to 770 in 2050 and 1,390 in 2100, more than a three-fold increase over the next 100 years. For comparison, the global energy system grew 16-fold over the past century. On a per person basis, this translates into an evolution from 70 GJ per capita in 2000 to 80 and then 130 in 2050 and 2100 – a doubling of per capita energy use in 100 years. It is important not to get too fixed on specific numbers. Whether the future size of the system is 860 EJ (a doubling) or 1,720 EJ (a quadrupling), most observers would agree that the system is likely to be significantly larger in 100 years. That information is sufficient for assessing system sustainability.

As in the past, increases in population and especially economic output will swamp declines in energy intensity.

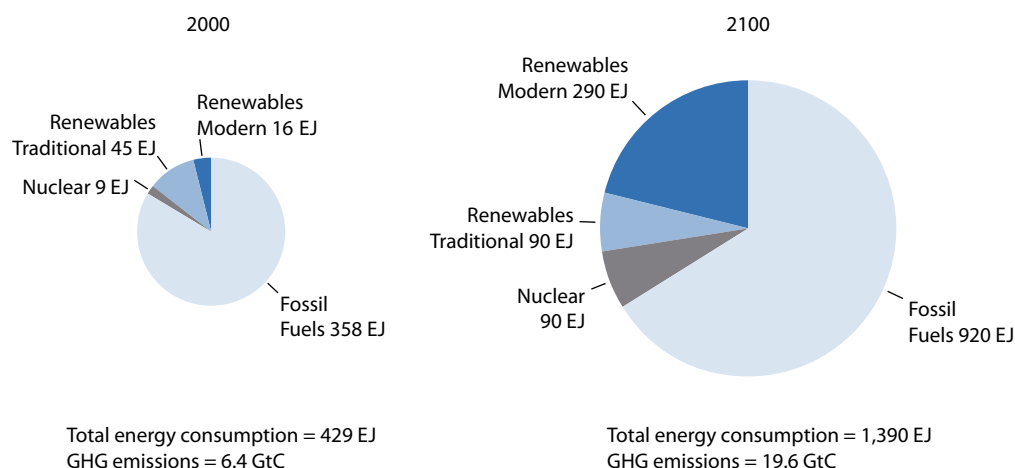
In setting my current-trends values for the relative contribution of primary forms of energy, I struggled with several major uncertainties. While some experts believe that production of oil and gas will drop off significantly in the next few decades because of supply constraints, others believe that advancing technological capabilities will enable us to sustain output and perhaps expand it. My current-trends assumption has oil and gas declining after 2050, albeit not as dramatically as some analysts predict.³

There is also much uncertainty about the relative prospects for nuclear and coal in meeting the widening gap between expanding energy use and stagnant oil and gas output. My current-trends scenario has nuclear and coal both growing significantly although coal's share grows the most, reaching 47 percent of total primary energy by 2100. This is because coal is often less expensive for making electricity and for producing the liquid and gaseous fuels that might replace declining oil and natural gas stocks. Remember that my projection sustains the general character and trends of the current energy system, which means that there are no major policy initiatives to achieve environmental or security objectives. As for renewables, my current-trends projection assumes an increase from 61 EJ in 2000 to 380 EJ by 2100, with most of this increase coming from modern uses of renewables such as wind and solar power and the conversion of biomass into gaseous and liquid fuels and electricity.

For assessing sustainability in this paper, my current-trends projection shows only energy-related CO₂ emissions, which are estimated to account for at least 60 percent of the climate change effect – ignoring other greenhouse gas (GHG) emissions such as nitrous oxides and methane. Figure 1 shows the resulting primary energy use and GHG emissions. Energy-related GHG emissions are projected to increase from 6.4 gigatonnes of carbon (GtC) per year in 2000 to 19.6 GtC in 2100. This substantial increase is consistent with many of the scenarios generated by the Intergovernmental Panel on Climate Change (IPCC) and other organisations.

³ That fossil fuels are plentiful – certainly in economic terms – is discussed in greater detail in Jaccard (2006, Chapter 5).

Figure 1. Current-trends primary energy and GHG emissions



My current-trends case would generate cumulative CO₂ emissions in the 100 years between 2000 and 2100 of about 1,200 GtC. For reference, the total anthropogenic CO₂ emissions from 1860 to 1995 are estimated at 360 GtC, of which 240 GtC were from fossil fuel combustion and 120 GtC from deforestation and other forms of land use change. According to the current models of carbon cycling between the atmosphere and the earth, the CO₂ emissions from my current-trends case would result in 2100 in a CO₂ concentration in the earth's atmosphere of over 650 parts per million by volume (ppmv) compared to the pre-industrial concentration of about 280 ppmv, and this concentration would keep increasing rapidly into the following century. Climate scientists suggest that concentrations above 450 ppmv could substantially affect the earth's climate.

4. The scope for zero-emission use of fossil fuels: the case of coal

My current-trends projection confirms today's wisdom that our energy system is unsustainable.

My current-trends projection confirms today's conventional wisdom that our energy system is unsustainable: combustion of the world's still-plentiful fossil fuels causes a continuous rise in atmospheric greenhouse gas emissions, which is just what scientists are warning us is unsustainable. However, there is also a growing awareness that abolishing fossil fuels is not necessarily the only or indeed even the best way of reducing GHG emissions. In this section, I summarise the latest evidence on how we might benefit from fossil fuels without emitting greenhouse gases into the atmosphere – what are referred to as 'zero-emission' fossil fuel technologies.

The body of literature on preventing carbon emissions from fossil fuel use seems to double every year, making it precarious to say anything definitive about which paths are more likely to emerge when the inevitable technological shake-out occurs.⁴ I provide here an overview of the major technological options that are likely to remain relevant in the years to come. Because coal is considered to be the most plentiful fossil fuel, but also the least desirable in terms of cleanliness of use, I focus below on options that can use coal as the primary energy source.

First, I must clarify the terminology. Although these options are generally referred to as 'zero emission', this is not entirely accurate. The emission prevention techniques that are currently under

⁴ For an overview of the options see Intergovernmental Panel on Climate Change (2005); Anderson and Newell (2004); International Energy Agency (2004); and <http://www.fossil.energy.gov>

consideration and whose costs are seen as reasonable all allow at least some escape of CO₂ into the atmosphere. A more precise term, therefore, would be 'near-zero-emission' processes. I stick with the term zero emission for simplicity and to signify that if any of these processes were to become the global norm, the effect would be a profound reduction in CO₂ emissions that would reverse the trend of rising atmospheric concentrations.

Capturing carbon as a solid or as CO₂ gas is one thing. Disposing of it is quite another. I focus first on processes for capturing carbon, then turn to the carbon storage question, and finish the section with a look at costs. Consistent with most current views, I focus on processes involved in capturing and storing carbon in the form of CO₂.

4.1 Carbon capture

Some commentators have suggested that the challenge of preventing CO₂ emissions from fossil fuel combustion is fundamentally different from the previous emission reduction challenges that the industry has dealt with – by virtue of the fact that CO₂ is an inescapable by-product of fossil fuel combustion. But academic and industry researchers seem unimpressed with this apparently daunting task, and have tackled this new challenge no differently than their predecessors solved earlier problems in reducing SO₂, particulates, NO_x and other emissions.

Academic and industry researchers have tackled carbon capture no differently than their predecessors addressed SO₂, particulates, NO_x and other emissions.

Indeed, one of the most promising approaches is to install yet another process for purging an unwanted emission from the post-combustion flue gases of fossil fuel electricity generation plants. Using existing technologies, it is possible to react the flue gas with a solvent that attracts the CO₂. The solvent then releases a stream of pure CO₂ in a separate stage, and finally is recycled back into the flue gas to repeat the process. The residual flue gas (mostly N₂, O₂ and H₂O) is released into the atmosphere. Some CO₂ escapes along with this gas.

This 'CO₂ scrubbing' technique can be integrated into new coal-fired power plants, and even retrofitted into existing plants if there is enough room. The energy required to run the capture process, however, would decrease the efficiency of a typical plant by 14 percent. To reduce this energy penalty, researchers are exploring ways to increase the efficiency of the scrubbing process by raising the CO₂ concentration in the flue gas from its typical level of 5-15 percent. This is achieved by increasing the oxygen content and pressure of the air fed into the combustion chamber through an air separation unit. Each option progressively increases the concentration of CO₂ and thus the efficiency of the chemical extraction process, but is only viable if the extra costs of concentrating oxygen are compensated by lower costs of CO₂ extraction. At an extreme, pure oxygen could be fed into the combustion chamber, resulting in a flue gas rich in CO₂ and water vapour. The latter could then be condensed in order to isolate the CO₂-rich gas stream. Because of the energy requirements of the air separation unit, this approach would decrease the efficiency of the coal plant by 11 percent.

Thermal power stations and some types of large industrial plants are stationary sources of CO₂ emissions for which this post-combustion capture approach would be relatively easy to implement. When it comes to smaller-scale fossil fuel combustion, however, the technological challenge is daunting. Carbon capture implies that equipment like home furnaces and personal vehicles would be fitted with miniature versions of the elaborate processes involved in CO₂ extraction, concentration and disposal in a coal power plant. This seems unlikely, although technological surprises cannot be rule out.

For total emission prevention, the more likely scenario is a substantial increase in the end-use role of electricity and hydrogen and a commensurate reduction in the end-use combustion of refined petroleum products (heating oil, transport fuels, butane, and propane) and perhaps even natural gas. Recognition of this has generated considerable interest in technologies and processes that produce from fossil fuels these two key forms of secondary energy while capturing CO₂ and other emissions.

Hydrogen has long been produced for industrial use, as a feedstock for ammonia production in fertiliser plants, but also for production of higher fraction fuels in oil refineries and, more recently, for the production of synthetic oil at oil sands plants in western Canada. Although hydrogen can be produced using any form of energy, most current production is based on the catalytic reaction of natural gas (mostly methane – CH₄) with steam – called ‘steam methane reforming’. Steam and methane are combined in a reactor at temperatures between 750 and 900°C where they react to form a synthesis gas comprised mostly of carbon monoxide (CO) and H₂. This gas is cooled and then combined with steam to provoke a water-gas shift reaction that splits the water to make even more H₂ while the oxygen combines with the CO to produce CO₂. The resulting gas mixture rich in CO₂ and H₂ is then split into separate gas streams using chemical solvents. Because there has been little concern in the past for capturing pure CO₂, the practice thus far has been to separate the H₂ but leave the CO₂ with other fuel gases for combustion, which means that all of the carbon in the natural gas eventually ends up as emissions of CO₂ and CO to the atmosphere.

If coal is the energy source instead of natural gas, and if the CO₂ is to be captured, some extra steps are required, but again these involve conventional technologies. Since coal has very little hydrogen, water is the major source of hydrogen in coal-based processes; coal provides the necessary energy for separating the hydrogen in water from oxygen.

The first step is coal gasification – subjecting the coal to oxygen and steam under pressure. This is the process developed in Germany in the 1920s and used today in South Africa to produce synthetic liquid fuels from coal, called *Fischer-Tropsch liquids*. Gasification produces a CO-rich synthesis gas comprised mainly of CO and H₂. The gas then enters a gas cleaning unit that extracts sulphur, mercury and other potentially toxic compounds (depending on the properties of the source coal) using solvents and other processes (an alternative configuration involves delaying some gas cleaning until after the next stage). Next, the gas is reacted with steam in the same water-gas shift reaction described for steam methane reforming, producing a synthesis gas rich in hydrogen and CO₂. A solvent, such as amine, is then used to capture CO₂ from the synthesis gas, leaving pure H₂ as the output. Researchers are trying to develop membranes that filter the CO₂ instead of capturing it with solvents; this could reduce the energy and material costs of separation.

Producing hydrogen from coal requires considerable energy, especially for generating the steam used in the coal gasification and the water-gas shift reaction.

Producing hydrogen from coal requires considerable energy, especially for generating the steam used in the coal gasification and the water-gas shift reaction. The first-law efficiency of the coal input to the hydrogen output is about 65 percent.⁵ Production of hydrogen from natural gas using steam methane reforming can achieve efficiencies above 80 percent, but this must be traded off against the higher cost of natural gas as both a hydrogen feedstock and energy source. Coal and water as the combined energy-hydrogen source are cheaper than natural gas and less risky with respect to price fluctuations and long-run price outlook.

⁵ First-law energy efficiency is measured by the ratio of the energy input to the useful energy output of a device. Although this is clearly a key aspect of energy efficiency, energy analysts point to the importance of second-law efficiency, which is measured by the ratio of the energy input of a device to the minimum amount of energy theoretically needed to perform a task. The differences and links between first-law and second-law efficiency are described in more detail and illustrated in Jaccard (2006, Chapter 4) in the context of discussing the role of energy-efficiency improvements in creating an enduring and sustainable energy system.

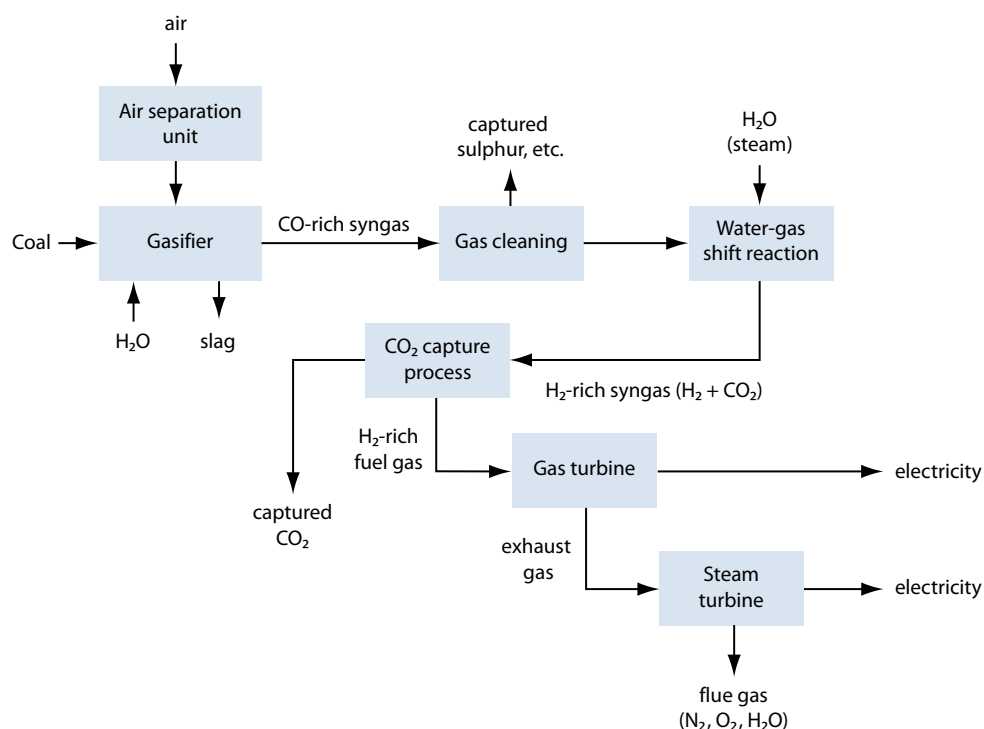
This coal gasification process can capture as much as 99 percent of sulphur and other pollutants, some of which can be processed into commercial chemicals. The slag residue from the gasifier can be used as a harmless material feedstock in road construction and perhaps other civil works.

While hydrogen has an important role as an industrial feedstock, it is rarely called upon to provide energy. Indeed, the development of hydrogen as a major source of secondary energy is hindered by the chicken and egg problem that faces all revolutionary changes in technology – hydrogen-using technologies need major expansion of hydrogen production and distribution facilities to justify their widespread dissemination, and *vice versa*. For this reason, most industry observers expect that coal gasification with carbon capture will first establish a market in electricity generation, a form of secondary energy that already has an established end-use market and delivery system.

The technological configuration that has captured the most attention is the integrated gasification combined cycle (IGCC) with carbon capture. As explained above, coal is gasified to produce a synthesis gas (labelled ‘syngas’ in Figure 2 below), but this time the hydrogen resulting from separation is combusted in a combined cycle unit (gas turbine and steam turbine) to produce electricity.

The technological configuration that captured most attention is the integrated gasification combined cycle with carbon capture.

Figure 2. IGCC to produce electricity with carbon capture



While its key technological components have all been in commercial operation for different applications, a single large IGCC plant has not yet been constructed; without penalties for CO₂ emissions, electricity companies had no motive to absorb the higher capital costs of an IGCC. To address this concern, the US government launched its *FutureGen* initiative in 2003 – a \$1 billion IGCC plant that would generate electricity (275 MW) but also serve as a laboratory for producing hydrogen from coal and for carbon capture and storage technologies. Since then, several governments have launched initiatives to build demonstration IGCC plants and some major electricity companies have announced plans to build large commercial IGCC plants for electricity production.

In presenting these major options, I have deliberately kept things simple. In each case only one form of secondary energy is produced: electricity or hydrogen. The gasification literature, however, is full of increasingly complex configurations in which a fossil fuel input (and biomass in some cases) is gasified into synthesis gas, which is then converted into not just electricity and hydrogen, but an array of synthetic fuels such as methanol, *Fischer-Tropsch liquids* (synthetic gasoline and diesel) and dimethyl ether, and perhaps even into various synthetic chemicals such as acetic acid, methyl acetate, ethylene, and propylene. These so-called poly-generation plants could be financially attractive because of their ability to generate value from so many of the process by-products and to achieve higher energy efficiency from using all available waste heat.

In terms of input energy source, the processes for zero-emission production of hydrogen and electricity could equally use natural gas or oil as the energy input instead of coal. Given their higher hydrogen content and greater energy density, these fuels can be more efficiently converted into hydrogen and electricity, but they are more expensive inputs than coal. Capital costs will also be different from one form of energy to another, including the equipment for controlling other pollutants. The choice of fuel will depend, therefore, on the interplay of these various factors, and will vary from one locale to another.

Biomass is also a potential fuel for energy conversion plants with carbon capture. In concert with carbon capture and storage, the use of biomass as input fuel creates a process with negative GHG emissions: extracting carbon from the atmosphere in photosynthesis to produce biomass, gasifying the biomass to produce synthesis gas, separating CO₂ from the synthesis gas and producing electricity or hydrogen from the hydrogen-rich gas, and then storing the CO₂. For some people this sounds too much like science fiction – a way for humans in future to manage the climate of the planet by increasing and decreasing the amount of CO₂ in the atmosphere. But technologically, this simply reflects our current capabilities.

Regardless of the input fuel or technology for carbon capture, this vision of zero-emission use of fossil fuels depends on whether the captured carbon can be permanently and safely prevented from reaching the atmosphere. Carbon storage is another field whose literature seems to double every year.

4.2 Carbon storage

For several decades some industries have been required to safely store or convert into marketable products various solid and gaseous wastes ...

For several decades, some industries have been required to safely store or convert into marketable products various solid and gaseous wastes. Particulates that are removed by electro-static precipitators and other collection systems (fly ash) find uses as material in structural fill, as dewatering and bulking agents, as road base materials, and as a feedstock in cement and concrete. In the case of sulphur, the conventional practice involves desulphurisation processes that recover sulphur in solid form (surface solids storage), which can have a market value for various processes and products. Recently declining prices in sulphur markets, however, have led to acid gas injection deep into geological formations – these acid gases are hydrogen sulphide (H₂S), CO₂, and other compounds that are mixed with natural gas in its reservoir and must be separated in order to produce marketable natural gas.

If our energy system is to continue to rely on fossil fuels while evolving into a zero-emission system, almost all carbon from fossil fuel use must be captured and stored. This means that we could conceivably require permanent storage capacity for the over 6,000 gigatonnes of carbon (GtC) in the estimated fossil fuel resource base. A carbon sink is the term used for a medium in which carbon is currently stored or potentially can be stored. The three major sinks that have been identified for carbon storage (or sequestration) are surface storage, ocean storage, and geological storage.

Surface storage of carbon can be achieved with natural and industrial processes. Living and dead biomass on the planet is already a major carbon sink. Forestry and agricultural carbon management can increase carbon storage in plants and soil by increasing or modifying vegetative cover and by altering tilling practices. By itself, however, this form of sequestration cannot prevent the build-up of greenhouse gases in the atmosphere because the mining of fossil fuels continually introduces to the earth's surface and atmosphere carbon that had been stored for millennia in sedimentary layers.

Another possibility for surface storage is for humans to extract elemental carbon from oil and natural gas directly and store it as solid carbon bonded with other elements to produce carbonate rocks. This may ultimately turn out to be the solution, but considerable research and development is required before we can know if this can be achieved at a reasonable cost on a large enough scale.

Ocean storage was initially seen as the most promising means of storing carbon. The oceans are already a major carbon sink, but their capacity to hold carbon can be augmented by pumping CO₂ into ocean depths from where it would not resurface because of its physical properties relative to seawater. At ocean depths below 800 metres, CO₂ changes from gas to liquid and below 3,000 metres it would have negative buoyancy relative to seawater, meaning that it would sink to the ocean floor. The potential storage capacity of this option far exceeds the carbon in the earth's estimated fossil fuel resources. However, the option raises environmental concerns about how acidity changes caused by increased CO₂ might affect deep ocean life forms. It is also expected that increased concentrations of CO₂ in the atmosphere will naturally increase the rate of CO₂ uptake in aquatic biomass, but an endeavour to manage this process is likely to be more difficult to control than land-based strategies.

Geological storage has garnered the most attention in recent years. For several decades, the fossil fuel industry has had experience in transporting CO₂ and injecting it into underground geological structures. In more than 70 sites worldwide, CO₂ is injected into oil reservoirs to increase pressure as part of enhanced oil recovery (about 20-30 million tonnes annually). CO₂ injection is also a means for enhanced natural gas recovery and for dislodging methane from deep coal deposits as part of coal-bed methane production. Finally, CO₂ is injected into sedimentary layers as part of acid gas injection.

... resulting in accumulated experience in transporting CO₂ and injecting it into underground geological structures.

A highly relevant demonstration is provided by the recent development of a major enhanced oil recovery project in western Canada. Since 2000, a plant in North Dakota has been shipping CO₂ to Saskatchewan for injection into an aging oil field to increase its yield by 30 percent. The North Dakota plant is a coal gasification facility that produces a hydrogen-rich gas for industrial uses and a stream of CO₂ as a by-product. Instead of being vented to the atmosphere, 20 million tonnes of the CO₂ are being shipped over the next 30 years to the Canadian field in a 320 kilometre pressurised pipeline. Industry, governments, and researchers are closely monitoring the project as it integrates all of the essential components of a zero-emission fossil fuel system – coal gasification, production of a hydrogen-rich fuel, capture of pure CO₂ in the gasification process, a long CO₂ pipeline, and geological storage of the CO₂.

This and other economically attractive projects indicate the feasibility of a concerted effort to sequester CO₂ in depleted oil and gas reservoirs. However, current and future depleted reservoirs have a combined carbon storage capacity of only 300-600 GtC, not nearly enough to contain all carbon from fossil fuels if these were to continue to dominate the global energy system through this century and beyond. Other research has widened the search for suitable geological storage sites to include the much more plentiful deep saline aquifers which underlie sedimentary basins at depths greater than 800 metres – far deeper than typical fresh water aquifers, which are found at 300 metres and less.

Contrary to the common understanding of the word aquifer, saline aquifers are not underground bodies of water, but rather porous rock infiltrated with highly saline water (oil and gas reservoirs are also usually in aquifers). Depending on pressure, porosity and other conditions, the pores of deep saline aquifers are capable of absorbing large quantities of CO₂, which would have a liquid-like density at these pressures. Researchers note the serendipitous association between fossil fuel deposits and deep saline aquifers, as they are co-located in sedimentary basins around the globe. While aquifers that are capped by an impermeable sedimentary layer are ideal, this is not essential for long-term storage. If injected far enough from the reservoir boundary, the CO₂ may eventually either dissolve into the aquifer water (hydrodynamic trapping) or precipitate as a solid carbonate mineral by reacting with the surrounding rock (mineral trapping). If dissolved into the aquifer water, the flow rates are such that in a million years most CO₂ would not have travelled more than 10-20 kilometres from the injection site. Efforts to estimate the total CO₂ storage capacity of deep saline aquifers are still crude, but the capacity is known to be huge. While initial estimates ranged from 3,000 to 10,000 GtC, of which two thirds are onshore and one third offshore, more recent analyses is converging around the middle of the range. Conveniently, this matches the planet's estimated carbon endowment in fossil fuels.

From its experience in enhanced oil and gas recovery, the petroleum industry is familiar with the properties of hydrocarbon saline aquifers, and with the dynamic properties of injected CO₂.

From its experience in enhanced oil and gas recovery, the petroleum industry is familiar with the properties of hydrocarbon saline aquifers, and with the dynamic properties of injected CO₂. But prior to the recent concern about climate change, there had been little interest in CO₂ sequestration in saline aquifers. Norway's implementation of a carbon tax of \$55 per tonne of CO₂ in the early 1990s motivated the *Sleipner* project in 1996. This is a project to inject CO₂ into a deep saline aquifer below the North Sea, not for enhanced oil or gas recovery, but simply to avoid the carbon tax. In this case, the carbon source is a reservoir of natural gas about 300 metres below the sea floor whose high CO₂ content must be reduced to meet market specifications. A process on the offshore platform uses a chemical solvent to separate CO₂ from the natural gas and then inject it into a saline aquifer 1,000 metres below the sea floor. The solvent is continually recycled in the process, and the cleaned natural gas is shipped by pipeline on the sea floor to northern Europe.⁶

Researchers, industry staff, and government officials now closely monitor the existing projects in which CO₂ is being geologically sequestered. Several new projects are in the planning stages or under development in Norway, Algeria, Australia, the United Kingdom and the United States.

Geological sequestration also requires the transport of CO₂, but there is extensive commercial experience since 1970 with long distance CO₂ pipelines, some of which extend more than 300 kilometres. The United States and Canada now have over 3,000 kilometres of pipelines carrying CO₂ from various sources for injection as part of enhanced oil recovery projects, resulting in the sequestration of about 50 million tonnes annually. These have operated without major concerns or incidents.

The generally positive views of energy technologists and earth scientists towards carbon capture and storage is important, but policy advisors know that no matter how low the risks of a particular technology, public perception is critical. Advocates of the zero-emission use of fossil fuels need to educate the public about the types of risks and their potential magnitude as well as engaging them in the planning and siting process of capture, transport, and storage facilities.

⁶ For an illustration of the process see:
<http://www.statoilnorge.no/STATOILCOM/SVG00990.NSF/web/sleipneren?opendocument>.

4.3 The future cost of carbon capture, transport, and storage

In the last decade, a great deal has been written on the projected costs of fossil fuel-derived energy with carbon capture and storage. While initial estimates varied substantially, the range has narrowed in the last few years as experts compare assumptions and share new information in conferences and international processes. A key document reflecting this work is the IPCC report on carbon capture and storage, which synthesises the extensive literature of recent years (Intergovernmental Panel on Climate Change 2005).

Carbon capture and storage cost estimates are constructed from individual estimates for the three separate components: capture, transport, and storage. Capture represents about 90 percent of the costs in most estimates.

Estimates have been generated for carbon capture in coal IGCC plants and natural gas combined cycle plants as well as for prospective coal and biomass poly-generation plants producing electricity, hydrogen, and synthetic fuels. These estimates vary in part because of different assumptions about fuel input costs (natural gas and coal), technology costs, regulatory costs, and the value of energy outputs (electricity, hydrogen, synthetic fuels, and process heat). They range from \$75 to \$150 per tonne of carbon (\$21 to \$42 per tonne of CO₂).

Because of the years of industry experience, there is little range in the estimates for the costs of CO₂ transport. Assuming a pipeline distance of 100-200 kilometres, the cost would be \$14-\$18/tC (\$4-\$5/t CO₂).

Sequestration costs can be negative or positive depending on whether the CO₂ has value for enhanced oil and gas recovery. The sequestration cost estimates therefore range from -\$20 to +\$30/tC (-\$6 to +\$9/t CO₂).

When all three components are combined, the total estimated cost ranges from \$70-\$200/tC abated (\$20-\$56/t CO₂). One way of interpreting these numbers is to convert them into estimates of their effect on the production cost of electricity and hydrogen. In the case of electricity generation, carbon capture and storage would add 2-3 \$-cents per kWh to the cost of electricity from an advanced coal plant, increasing its total production cost to 6-9 \$-cents/kWh (assuming that sulphur, fine particulates, and other emissions are also captured). In the case of hydrogen production, carbon capture, transport and storage would add about \$2-4 per gigajoule over the current cost of producing hydrogen from natural gas reforming (when the natural gas price is at \$3/gigajoule).

When the objective is to shift to a clean energy system over a long time period, these costs do not present an overwhelming barrier. Electricity prices currently vary by at least 3 \$-cents/kWh from one jurisdiction to the next as a result of regional resource endowments and historical investment choices (hydropower, nuclear, coal, natural gas, renewables). Indeed, the move towards market prices in some jurisdictions has been associated with short-run price fluctuations far exceeding 3 \$-cents/kWh.

But whether or not our current preference for fossil fuels should be sustained as we shift towards a cleaner energy system depends on how this primary energy option compares to others. I now turn to this task by conducting an evaluation that includes cost information in conjunction with

Carbon capture and storage would add 2-3 \$-cents per kWh to the cost of electricity produced from an advanced coal plant.

the other real-world considerations that might influence our choice of energy alternative, such as international politics, divisions between industrialised and developing countries, regional and local politics, and public perceptions of risk. I especially focus on coal, although the analysis applies to all fossil fuels.

5. A multi-criteria assessment of coal vs. alternative non-fossil fuel options

In this section, I compare fossil fuels, efficiency, nuclear, and renewables on the basis of their performance against three criteria: projected financial cost, extreme event risk, and geopolitical risk.

5.1 Projected financial cost

The cost of energy efficiency is controversial, with some advocates arguing that reducing energy use by 30-75 percent in industrialised countries is profitable at current prices. In part, advocates build their case on the presumption that there are easy to remove barriers to energy efficiency – a hypothesis critically reviewed, for example, by Schleich (this volume). Indeed, a substantial body of research suggests that this analysis overestimates technically achievable efficiency gains, underestimates risks associated with new efficient technologies with lengthy payback periods, underestimates welfare costs to consumers of adopting technologies and behaviours that are not perfect substitutes for current practices, overlooks cost decreases to supply technologies that make efficiency comparatively more expensive, and overlooks new profit seeking practices and consumer preferences that by increasing energy demand partly offset efficiency gains.

It is increasingly recognised by independent energy analysts that only a fraction of the so-called profitable energy efficiency actions are likely to be economically beneficial.

Thus, it is increasingly recognised by independent energy analysts that only a fraction of the so-called profitable energy efficiency actions are likely to be economically beneficial on the basis of financial costs alone (excluding externalities). Beyond this amount, some additional energy efficiency will cost only a modest amount, so effort to realise some of this may become financially justified. But only if the development of clean secondary energy leads to significantly higher energy prices will a substantial increase in the rate of energy efficiency improvement occur. Is this likely to happen?

The energy and environment literature is rife with estimates for future energy supply costs, much of it driven by the intense focus on reducing CO₂ emissions. I have reviewed several studies in the process of developing my own set of numbers for the costs of producing electricity, hydrogen, low-emission synthetic fuels, and biofuels.⁷ My cost estimates are based on these studies, but also incorporate my reading of the particular constraints and opportunities facing each option over the course of this century – resource constraints, land-use constraints, regulatory constraints, infrastructure costs, and potential cost reductions due to economies of learning and economies of scale. Adjustments such as these are necessary because most cost estimates are focused on the technologies and resources that are seen to be most plausible for energy supply investments over the next 20–50 years. To produce a crude estimate that extends out 100 years, additional assumptions about these long-term constraints and opportunities are required. I explain the key assumptions behind each of my numbers.

Table 1 presents my estimates for the cost of generating electricity from alternative supply sources over the coming century. The values are in \$-cents per kWh in prices of 2000. Confidence in the

⁷ Key studies include the following: Goldemberg (2000); Goldemberg and Johansson (2004); Intergovernmental Panel on Climate Change (2001); Intergovernmental Panel on Climate Change (2005); Gale and Kaya (2003); and Sims *et al.* (2003).

values is obviously higher for the earlier decades of the century. The range for each estimate indicates both the increase in uncertainty further into the future and the likelihood of movement as various constraints and opportunities come into play over time. These costs are assumed to reflect the costs for each option were it to experience large-scale development – which requires consideration of both cost-reducing and cost-increasing aspects.

Table 1. Projected electricity cost (\$-cents per kWh in 2000 prices)

Coal PC post-combustion	Coal IGCC	Natural gas CCGT	Nuclear	Hydro	Wind	Biomass	Solar-PV
6–7	5½ – 6½	5½ – 6½	6–10	6–8	6–8	6–8	15–20

Notes: PC = pulverized coal; IGCC = integrated gasification combined cycle; CCGT = combined cycle gas turbine; PV = photovoltaic. Assumed input prices are coal \$1.5–3/GJ, natural gas \$5–7/GJ, and biomass \$2–5/GJ.

All three fossil fuel technologies include the full cost of carbon capture, transport, and storage – reducing carbon emissions from each source by about 90 percent. They also include desulphurisation, low nitrous oxide emissions, and capture of particulates in the case of coal combustion. The two coal options are combustion of pulverised coal for a standard steam turbine with post-combustion capture of CO₂ and other emissions, and coal gasification with CO₂ capture from the resulting synthesis gas, which then feeds a combined cycle gas turbine. Some studies show natural gas as the cheapest fossil fuel option for generating zero-emission electricity, but my cost estimate reflects the transition over the course of the century from conventional natural gas towards higher cost unconventional sources (matching, perhaps with a lag of a few decades, that of oil) as well as the effect of the more recent trend for international trade in liquefied natural gas to bring natural gas prices upward into line with oil prices on a per unit of energy basis. Given the large current supplies, the cost of coal is unlikely to increase significantly over the course of the century, although it will experience short-term fluctuations whenever price instability affects a key substitute such as oil or natural gas.

The wider cost estimate for nuclear power of 6–10 \$-cents/kWh reflects the diversity in how countries develop this technology, disputes about its full costs, and uncertainty about its future costs. My estimates are intended to include the full costs of siting new facilities, treating and permanently storing all nuclear waste, and operation of international institutions and monitoring mechanisms to ensure a safe worldwide expansion of the technology. Some experts argue that inclusion of all these costs will push the estimate into the higher end of my range and perhaps beyond.

The table presents four renewable alternatives for electricity generation – hydro, wind, biomass and solar PV. The wide range in the cost estimates for each renewable reflects the uncertainty as to how large-scale development will affect the countervailing factors causing cost reductions and cost increases. Renewables advocates focus on the economies of scale and economies of learning that will lower costs as renewables achieve a growing share of the global energy system. Sceptics caution, however, that there will also be upward cost pressures if renewables were to become the dominant source of energy. For hydropower, windpower and geothermal among others, development occurs first at the most favourable sites and then proceeds to less favourable, higher cost sites. The low energy density of most renewables means that wide-scale expansion will increasingly confront competition for land with non-energy uses, as in the case of biomass. Because many renewables provide only intermittent energy, the additional costs of energy storage must be included as renewables provide a larger share of energy supply. This can lead to substantially higher costs unless research and development realises significant gains in reducing the costs of non-hydro energy storage.

The low energy density of most renewables means that wide-scale expansion will increasingly confront competition for land with non-energy uses.

Table 2 presents my estimates for the cost of producing hydrogen from alternative supply sources over the coming century. As with electricity, these cost estimates reflect the cost of an option was it to experience large-scale development – which requires consideration of both cost-reducing and cost-increasing aspects. The range for each estimate indicates both the increase in uncertainty further into the future and the likelihood of upward or downward change as various constraints and opportunities come into play over time. The wider range of the cost estimates compared to those for electricity reflects the lack of experience with large-scale hydrogen production.

Table 2. Projected hydrogen cost (\$ per GJ in 2000 prices)

Coal gasification	Natural gas steam-methane reforming	Nuclear electrolysis of H ₂ O	Wind/hydro electrolysis of H ₂ O	Biomass gasification
8–10	8–10	18–25	18–25	10–15

Notes: Assumed input prices are coal \$1.5–3/GJ, natural gas \$5–7/GJ, and biomass \$2–5/GJ. For electrolysis, see Table 1 for assumed electricity prices from each source. GJ of hydrogen based on ‘higher heating value.’

Unlike in the case of electricity, there are significant cost differences. Producing hydrogen via gasification or steam reforming is substantially less expensive than via electrolysis of water using electricity. Unless there is a major breakthrough in electrolysis processes, the gasification of coal and the steam methane reforming of natural gas – both with carbon capture, transport, and storage – offer the least costly means of producing hydrogen. Biomass gasification offers the lowest cost method of producing hydrogen from renewables, but it still has higher costs than coal gasification because of capital cost differences and land competition were this option to become the dominant means of producing hydrogen. Other candidate processes for hydrogen production, such as the thermal splitting of water, are excluded from the table as their costs will not be competitive without a major technological breakthrough.

If hydrogen is to play a significant role in the global energy system, it is likely to be especially important as a transportation fuel, initially in large urban areas.

If hydrogen is to play a significant role in the global energy system, it is likely to be especially important as a transportation fuel, initially in large urban areas. Given all of the uncertainties about long-term hydrogen transport and storage capabilities, and the resulting costs, the estimated cost of shifting to hydrogen for the services provided by personal vehicles is highly uncertain. This requires a set of cost estimates for fuel production, fuel delivery, vehicle engine platforms, and the efficiencies at each link in the chain. Some analysts suggest that even in the long-run the costs of fuelling personal vehicles with hydrogen will result in double the energy service cost – on a person-kilometre-travelled basis – compared to gasoline and diesel. Others suggest that within a few decades these costs could be quite comparable (see, for example, Ogden *et al.* 2004). Again, if this latter case is true, the prospects for reduced energy use due to efficiency and mode switching away from personal vehicles will be diminished accordingly.

Stepping back to compare all of energy supply costs, there are some situations in which the competing sources of supply are similar in cost. This suggests that other criteria will play a role in our choice of energy option. I focus below on how each option compares in terms of extreme event risk and geopolitical risk.

5.2 Extreme event risk

Both energy efficiency and renewables appear to have a comparatively clean slate when it comes to extreme event risk. Even the risks of failure by large hydro dams are well understood by experts and there is considerable public confidence in this expertise.

Nuclear power is especially vulnerable to the tendency for the public to put extra weight on catastrophic outcomes even though these have extremely low probabilities of occurrence. This can seem irrational to nuclear advocates, but it is consistent with a rational risk-averse strategy. Some analysts suggest, moreover, that nuclear power faces an additional burden in that the type of extreme event it is associated with is particularly frightening to many people. The unseen radiation exposure associated with a catastrophic nuclear accident signifies potential damage to the human genetic code and possible mutations in future generations. Dread of this type of extreme event is profound, even among well-informed and well-educated people, and this represents a serious handicap for nuclear relative to its competitors, especially for the siting of new plants. In the United States, for example, even if the federal government strongly supports the establishment of nuclear power facilities at new locations, local authorities have considerable control over site permitting and opposition groups have numerous legal and public relations means at their disposal.

Because of the potentially frightening character of a nuclear catastrophe, there is also a fear that nuclear facilities are ideal targets for terrorist attack. This possibility can appear to increase the probability of occurrence for what is otherwise an extremely unlikely event.

Fossil fuel use can be associated with various types of extreme events, although none of these appear to be at the same level of significance for the public and decision makers as the risks of a major nuclear accident. There have been marine oil spills, refinery explosions, pipeline explosions, and coal mining accidents (slides, mine collapse or explosion). However, the risks are mostly local and well understood, and can be diminished by efforts to tighten safety standards and to mitigate impacts in the aftermath of an accident. While an emerging risk from fossil fuel combustion is the possibility of runaway climate change from accumulated greenhouse gases, this risk does not apply to the zero-emission fossil fuel option.

As I noted above, geological storage of CO₂ is in its early stages, making it precarious to anticipate how the risks of large-scale development might be perceived by the public one or two decades from now. However, CO₂ has been injected underground for decades as part of enhanced oil recovery and acid gas injection. Localised risks from a significant leak do not appear to be of a different magnitude from the kind of risk the public faces every day from oil and gas pipelines, petroleum refineries, gas processing plants, enhanced oil and gas recovery, transport by truck, rail and ship, and even the use of oil and gas inside public and private buildings. The industry has a good safety record, but major accidents occur from time to time, and these do not lead to major shifts in opinion against the use of fossil fuels. Slow leaks of CO₂ could affect the achievement of greenhouse gas reduction objectives, but experts suggest that these slow leaks can be offset by a modest quantity of biomass gasification with carbon capture and storage.

5.3 Geopolitical risk

It is often assumed that renewables are like efficiency in that as domestic energy alternatives neither poses geopolitical risk. While this is true for efficiency, the apparent immunity of renewables from geopolitical risk might simply reflect their small share of the global energy system. Would that change if renewables were to dominate? In a renewables energy future, would each country become autarkic, meeting virtually all of its energy needs from indigenous renewable resources in a small-is-beautiful future? Or, would some countries have substantial advantages that enabled them to profit by exporting renewables-based electricity, hydrogen, and synthetic fuels to countries less favourably endowed?

It is often assumed that renewables are like efficiency in that as domestic energy alternatives neither poses geopolitical risk.

Although some advocates claim that the development of renewables would result in uniform energy costs between countries and the end of significant energy trade, the evidence suggests otherwise. Renewable resource endowments on the planet are as geographically heterogeneous as fossil fuel resources. Perhaps Mongolia would export wind-based electricity to China. Perhaps Middle-East countries, their conventional petroleum resources declining, would cover large areas of desert with PV arrays, exporting electricity directly or using it to produce hydrogen for export via pipeline and tanker. Perhaps biomass-rich countries would produce electricity and hydrogen and synthetic fuels for export. Under such heterogeneity of resource endowments and interdependence from trade, it seems plausible that renewable energy could be vulnerable to exploitation as a pawn of geopolitics just as water, another vital renewable resource, is today.

The geopolitical risks of nuclear power, in contrast, are widely agreed upon. Several times over the past decades, the dissemination of nuclear technology, ostensibly for domestic power production, has been associated with diversion to nuclear weapons development. Israel, India, and Pakistan cached weapons production under their domestic nuclear power programmes. Iraq tried to do this in the 1980s until Israeli fighter jets destroyed its main facility. North Korea and Iran are contemporary threats. Dominant powers in the world are wary that disgruntled or ambitious governments in unstable regions may try to develop nuclear weapons in order to improve their bargaining power, and that even terrorist organisations might try this.

Geopolitical risk presents a substantial barrier to the global dissemination of nuclear power, especially to poorer regions of the planet.

This risk presents a substantial barrier to the global dissemination of nuclear power, perhaps especially to the poorer regions of the planet where electricity demands should grow the fastest. Use of nuclear power may increase in OECD countries, if there is sufficient demand, if it can out-compete other energy sources (in competitive markets), and if local populations permit the siting of new plants. It can also grow in countries like Russia, India, and China – although the United States and other global powers are likely to be concerned about safeguarding measures if the nuclear industry grows to dominant levels in these energy systems. But its development in the Middle East, Africa, and parts of Asia is less likely to be acceptable to the United States and the other major powers for some time yet.

Some would argue, however, that the geopolitical risk of global dissemination of nuclear energy is small compared to the risk of reliance on petroleum imports – meaning that the geopolitical criterion actually works in favour of nuclear power. This was the rationale behind the French and Japanese nuclear programmes in the 1980s. Political instability in the oil-rich Middle East is correlated with periods of oil price instability and threats to economic growth: the Arab-Israeli war and oil embargo in 1973, the Iranian revolution in 1979, the Iraqi invasion of Kuwait and subsequent expulsion by NATO in 1991, and the Anglo-American invasion of Iraq in 2003.

With its extensive petroleum resources, Russia is less exposed to international oil market turbulence. There is, however, considerable concern in the United States, Europe, Japan and increasingly China and India that the geopolitical risks of oil will intensify, perhaps rapidly, over the coming decades as global dependence on OPEC and especially Middle-East oil increases. Oil resources in the United States, China, and Europe (North Sea) are being depleted while oil imports by industrialised countries and many developing countries like China are increasing rapidly. Both the United States and China are projected to experience a substantial growth in oil import dependence over the next decades if current trends continue.

While some people lump all fossil fuels together with oil when discussing geopolitical risk, others see a sharp difference. As it grows in significance, natural gas has achieved comparable status to oil in some respects, and this may include geopolitical risk. Europe feels increasingly that its natural

gas supplies from Russia are insecure. One response is to increasingly rely on liquefied natural gas, which allows for supply from anywhere in the world.

Coal seems to pose virtually no geopolitical risks, either currently or in the foreseeable future. This fossil fuel is distributed widely around the planet, with key countries like the United States, Russia, and China being particularly well endowed, and India also owning substantial resources.

The evaluation of the geopolitical risks of fossil fuels must be understood in its full dynamic. While conventional oil provides the quintessential example of geopolitical risk, switching away from all fossil fuels makes little sense if the goal is to reduce this risk. Coal and natural gas are plentiful in many regions of the world. Moreover, major deposits of unconventional oil, ultra heavy oil and oil shale, are located far from the Middle East.

The evaluation of the geopolitical risks of fossil fuels must be understood in its full dynamic.

5.4 Multi-criteria comparison of the energy options

If these three criteria are dependable indicators of the key factors to consider when evaluating our primary energy options, they show that no option is superior on all counts. The choice is not obvious. One might conclude that we can and should pursue all four options with equal vigour. But if history is any guide, this is rarely a dependable approach – and the world rarely unfolds this way anyway. There are usually winners and losers, or at least options that fare better even though all are pursued to some extent. In this sub-section, I compare the options in terms of these criteria in order to generate my own assessment of the path that humanity is likely to follow if its goal is to achieve a clean and enduring energy system.

I summarise each energy option’s performance against the evaluative criteria in Table 3. Energy efficiency and renewables are generally free of extreme event risk and geopolitical risk. Some efficiency and renewables are economic relative to zero-emission fossil fuels and nuclear, but their costs rise if more ambitious growth is pursued in too short a timeframe. Greater use of renewables, especially if rushed during the next few decades, will entail higher costs because renewables are particularly associated with new technologies that need more R&D and that have not yet benefited from the economies of scale and economies of learning that result from widespread commercialisation. As commercialisation progresses, the competitive position of renewables could improve, but this depends on whether exhaustion of the most favourable sites occurs faster than innovation and commercialisation can lower costs. The eventual cost of large-scale energy storage is a big uncertainty for the intermittent renewables like wind and solar, which could lead to much higher costs as their market share grows.

Table 3. Multi-criteria comparison of energy options

	Projected financial cost	Extreme event risk to environment and humans	Geopolitical risk
Efficiency	Some competitive. Costs rise steeply for dramatic reductions.	No risk.	No risk.
Nuclear	Slightly higher cost.	High perceived risk.	High risk.
Renewables	Some competitive, some higher cost. High costs if dramatic expansion in short time period.	No risk.	No risk yet. Moderate risk possible with larger scale.
Fossil fuels	Competitive. Slightly higher cost with carbon capture and storage.	Moderate to low risk.	Oil perceived high risk. Coal – low risk.

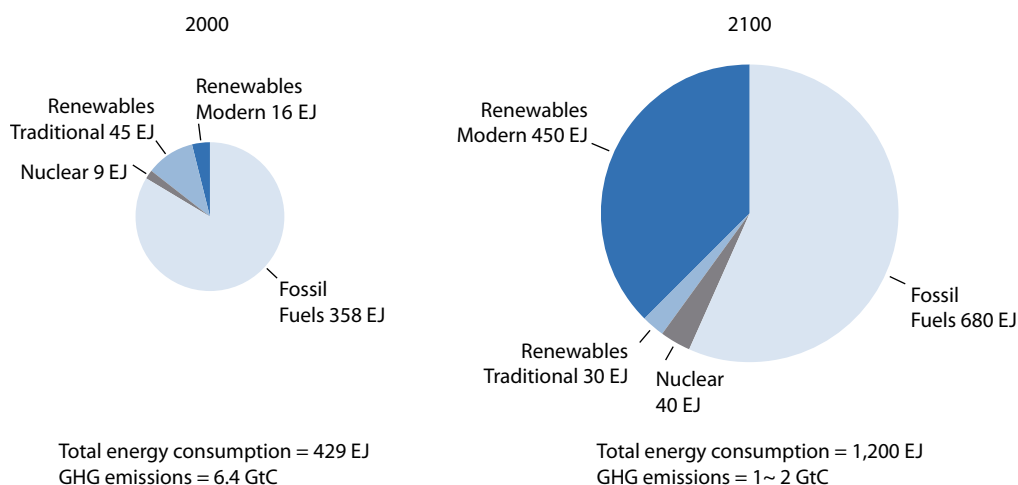
Zero-emission fossil fuels should remain economically competitive, given the plentiful resource base, the opportunity to substitute among fossil fuels with modest increases in production costs, and the reasonable cost of producing hydrogen, electricity and synthetic fuels in zero-emission processes. Conventional and unconventional oil may also play a role in the zero-emission production of electricity and hydrogen depending on the growth of these reserves as energy prices rise. With a growing role for coal, unconventional oil and unconventional natural gas, the geopolitical risk associated specifically with crude oil should diminish for fossil fuels as a whole. Extreme event risk should not be great, although there is still some uncertainty about the local risks of carbon storage in geological formations.

My multi-criteria comparison suggests that nuclear power has a low chance of pushing aside fossil fuels and renewables in order to dominate the global energy system ...

This multi-criteria comparison suggests that nuclear power has a low chance of pushing aside fossil fuels and renewables in order to dominate the global energy system. Given its negative scores in the areas of extreme event risk and geopolitical risk, nuclear probably needs to be substantially cheaper than the alternatives if it is to have a chance of playing a dominant role in the global energy system for the foreseeable future. It does not have this cost advantage today and appears unlikely to achieve it during the next 50 years unless fossil fuels are deliberately abandoned while efficiency and renewables are pursued too aggressively. The best hope for nuclear is if large, relatively stable countries like China and India make the industry the centrepiece of their national energy strategies, but even expansion in these two countries would be insufficient for nuclear to realise a dramatic increase in its share of the global energy system.

To recall from Figure 1, in my current-trends projection nuclear grows tenfold over this century, from 9 to 90 EJ. On the basis of this multi-criteria comparison, I revise this downward in my sustainable energy projection – pictured in Figure 3 – to 40 EJ, which still represents a five-fold expansion, attaining 2,000 plants worldwide in comparison to the current 430. Most of this expansion would occur in the latter half of the century, keeping the share of nuclear in total electricity generation not far below its current 17 percent market share.

Figure 3. The sustainable fossil fuel future



Regardless of whether one favours renewables, nuclear power, or fossil fuels, most people agree in principle that energy efficiency has highly desirable attributes and should be pursued. There are, however, several challenges to the achievement of rapidly declining primary energy intensity (the ratio of primary energy to world economic output), which is the goal of our energy efficiency efforts.

First, a rapid decline in energy intensity is not always possible or desirable. In my current-trends projection, energy intensity declines by 0.8 percent annually during the century and still the global energy system grows to more than three times its current size. Yet global energy intensity was constant between 1850 and 1950, and only declined at an average annual rate of 0.7 percent during the last several decades, a period with recurrent expectations of rising energy prices and widespread government and utility energy efficiency efforts. Even if the rate of intensity decline could somehow be sustained through the century at the high rate of 1.2 percent annually, the global demand for primary energy would still grow to 920 EJ, more than double its current level.

Second, economic growth in developing countries can require a lot of energy for the steel, cement and other heavy industries whose output is required to construct buildings, factories and infrastructure. Growing energy demand from final consumers will cause strong upward pressure on energy intensity, again especially in developing countries where the increasing demand for heating and air conditioning of larger living spaces, all sorts of appliances, and greater personal mobility will strongly correlate with rising incomes. The rising energy demand associated with China's rapid economic growth of the past two decades illustrates this link.

Third, an energy system dominated by conventional oil and natural gas is able to take advantage of the high energy density and high conversion efficiency of these two primary forms of energy. As that system evolves towards unconventional oil, unconventional natural gas, coal, and renewables with storage, energy production and conversion activities will consume more energy. Oil sands extraction requires significant inputs. Zero-emission conversion of coal to electricity has a lower efficiency than conventional, emitting technologies. Offshore windfarms require long transmission lines that lose energy as a function of distance. The conversion processes required for providing energy storage alongside intermittent renewables will also use of lot of energy. Our exhaustion of the highest quality energy endowment and our demand for cleaner secondary energy will create, for global energy intensity indicators, an upward push to counter the normal downward push resulting from technologies becoming more energy efficient.

... while an energy system dominated by conventional oil and gas is able to take advantage of high energy density and high conversion efficiency of these two primary forms of energy.

Fourth, energy efficiency is a double-edged sword in that efficiency improvements lower the operating cost of energy services, which can result in a rebound in the demand for the service or some related service. Efficient light bulbs lower the cost of lighting, which may not increase the demand for interior lighting but may surface as increased demand for decorative and security lighting. Rebound also occurs because of the harder-to-measure connection between improvements in energy productivity and the invention of new energy using services and devices – and example being the rapid spread of backyard patio heaters in wealthier northern countries. Some research suggests that this phenomenon will be a significant counterweight to energy efficiency efforts.

These factors make it difficult for policies in favour of energy efficiency to make great gains in accelerating the normal tendency for energy intensity to decline gradually. Thus, under most scenarios of population and economic growth, the global energy system in 2100 is unlikely to be much below 1,200 EJ. In the absence of dramatically higher energy production costs, the only way to achieve this outcome would be via higher energy taxes and forceful energy efficiency regulations. Governments have not been able to sustain these types of policies in the past, and this would be especially difficult to justify if zero-emission energy supply were not particularly expensive.

For my sustainable energy projection in Figure 3, I assume that the global energy system in 2100 will require 1,200 EJ of primary energy instead of the 1,390 EJ of my earlier current-trends projection

(Figure 1). This will require an average decline in the energy intensity of the global economy of about 1 percent per year through the century. The primary energy system therefore increases by almost threefold, which is still a dramatic slowing of growth compared to the 16-fold expansion during the previous century.

Given the limitations of nuclear power and energy efficiency, I conclude that renewables and zero-emission fossil fuels will especially compete for dominance over the coming century. Renewables may appear to many people to be more attractive in terms of both cleanliness and endurance, but zero-emission fossil fuels are likely to have a cost advantage in most circumstances as well as the additional advantage that they currently dominate the global energy system. Even with rapid growth, renewables would be hard pressed to overtake fossil fuels by the end of the century given the small base they must start from in what will remain a rapidly growing global energy system. There would be a greater possibility if renewables were significantly cheaper than zero-emission fossil fuels, thereby motivating business and consumers to switch as soon as they had the chance. Instead, the evidence suggests that zero-emission fossil fuels will remain economically competitive with renewables because of the abundance of exploitable reserves of unconventional oil, unconventional natural gas, and especially coal – which will impede the ability of renewables to replace them quickly. Even if those who emphasise the global significance of ‘peak oil’ are correct, and conventional oil production soon begins an inexorable decline, this should have no significance for the competitive position of fossil fuels relative to renewables in the early decades of this century. Conventional oil is but a small component of the aggregate fossil fuel resource, and its potential fossil fuel substitutes may be more expensive per unit of fuel delivered, but not greatly so. Also, a more rapid expansion of renewables will more quickly confront the problems of energy storage and land use conflicts instead of allowing research and development the time to produce innovations that could address these challenges and reduce costs. In these circumstances, an effort to push the market share of renewables substantially beyond the already rapid growth in my current-trends projection is likely to raise the total costs of the energy system with no appreciable benefit in terms of the key trade-off criteria for choosing among energy options. It is difficult to envision the political will for such an effort.

With environmental policies raising the cost of electricity from fossil fuels, renewables will find opportunities to compete.

Since greenhouse gas emissions, especially carbon emissions, have a dominant place in current discussions about energy sustainability, I assess in greater detail how energy options and specific technology choices could affect the evolution of these emissions. Coal-fired electricity plants produced almost one third of anthropogenic carbon emissions in 2000, and this share grows dramatically in my current-trends projection. In the next decade or so, efforts to increase the role of wind, hydropower, and natural gas in electricity generation can only slow slightly the growth of carbon emissions relative to the current-trends projection. However, on a 10-50 year timeframe, carbon capture and storage technologies will pass from the demonstration stage to commercial dissemination – provided there are policies to motivate the installation of these higher cost technologies and processes. Once the technology is well-proven, it becomes much easier for governments in the middle decades of the century to enact more forceful policies that lead to universal compliance with carbon capture and storage requirements at coal-fired and perhaps natural gas-fired electricity generators. With these policies raising the cost of electricity from fossil fuels, renewables will find opportunities to compete. But even the high growth rate I envision for renewables will not sweep away fossil fuel dependency over the course of the century.

For the transport of people and goods – the other great source of carbon emissions – the picture is more complicated. It is important to assess not just the end-use emissions of the transport mode (personal vehicle, public transport, ships, trains and planes) but also emissions that occur upstream

in the production of the electricity, hydrogen or hydrocarbon fuels used in the mode of transport. This is why some analysts argue that gasoline combusted in efficient internal combustion engines will still be desirable because the life-cycle emissions will be less than those of electric vehicles recharged from a fossil fuel-based electric grid or hydrogen fuel cell vehicles using hydrogen produced from fossil fuels (both in energy systems that lack carbon capture and storage). The case for efficient internal combustion engines is even stronger if some of the hydrocarbons it uses are produced from biomass.

As for the transport of people and goods, the case for efficient internal combustion engines is even stronger if some of the hydrocarbons it uses are produced from biomass.

However, because my clean energy future does not allow the use of fossil fuels without carbon capture and storage, I can focus on the relative viability of only those major technology-energy alternatives for transport energy that have close to zero life-cycle emissions. If the global carbon constraint is severe, biomass may garner an exclusive role in the production of liquid fuels for air travel (depending on the willingness to accept hydrogen combustion for air transport). But for other applications, the alternatives for substantially cleaner transport energy appear to be equally viable at this point. One alternative is super-efficient internal combustion engines that combust lower emission hydrocarbon fuels like natural gas or synthetic fuels from biomass and fossil fuel feedstocks (the latter with partial carbon capture and storage) rather than gasoline. But if global mobility trends continue as I project them to, this alternative cannot be dominant because it will not satisfy my sustainability requirements for greenhouse gas emissions and local air pollutants.

A second alternative is hydrogen fuel cells with the hydrogen mostly produced by gasification of fossil fuels with carbon capture and storage, which is the cheapest zero-emission way of producing hydrogen for the foreseeable future.

A third alternative is the wide-scale adoption of efficient plug-in hybrid engines that substantially increase the role of electricity in fuelling mobility of goods and people. This alternative could be superior under two conditions. For one thing, carbon and/or local pollution constraints require end-use technologies that are virtually zero-emission (thus ruling out the reliance on stand-alone internal combustion engines). For another, hydrogen production costs, hydrogen storage problems, and/or high fuel cell costs offset the benefits of more efficient hydrogen production directly from fossil fuels (as opposed to producing electricity) and the efficient hydrogen fuel cell engines. In this case, there is a chance for market dominance by high efficiency plug-in hybrid engines fuelled primarily by expanded production of zero-emission electricity from fossil fuels and renewables (see, for example, Hoffert *et al.* 2002 and Ogden *et al.* 2004).

What is important from a primary energy perspective, however, is that zero-emission fossil fuels have a good prospect for playing a significant role in all three of these technology-energy alternatives for transport of people and goods. If this assessment proves to be correct, fossil fuels would continue to dominate both electricity generation (currently the domain of coal and natural gas) and transport fuels (currently the domain of oil). This technology-energy evolution at the secondary energy level would occur in step with an evolution at the primary energy level from conventional oil, conventional natural gas, and coal in the current system to unconventional oil, unconventional natural gas and yet more coal as the century progressed. If it turns out that potential fossil fuel reserves are more limited than current assessments indicate, then growing energy demand will lead to gradually rising fossil fuel prices and eventually open the door to a more rapid growth of renewables in the later decades of the century – as well as greater opportunities for energy efficiency and perhaps nuclear.

In spite of these competitive challenges for renewables, I project that their output in a sustainable energy future exceeds that of my current-trends projection – even though this is a scenario in which they already experience extremely high growth rates through the century. While the current-trends projection has renewables reaching 380 EJ by 2100, I now project that with a strong push to a cleaner energy system they can reach 480 EJ by 2100. This means that in my sustainable energy future in Figure 3 the contribution in 2100 from renewables alone exceeds today's entire global energy system of 429 EJ in 2000.

6. Overview and policy implications

In this paper, I describe the technologies that would permit humanity to continue to use fossil fuels even while radically reducing the global energy system's GHG emissions over the next 50 to 100 years. I estimate the likely costs of producing zero-emission energy from fossil fuels and then compare these with the projected costs of meeting our energy needs from nuclear power and renewables in the decades to come. But to make a more realistic comparison of our energy options, to this cost information I then add an assessment of the extreme event risks and geopolitical risks associated with each supply option.

My resulting multi-criteria comparison of our energy options suggests that both nuclear power and energy efficiency are constrained in their potential over this century to deal with the rapidly rising demand for energy services. Renewables and zero-emission fossil fuels, especially coal in the latter case, are likely to compete for dominance of the global energy system. While the market share of renewables will grow significantly, these are unlikely to unseat fossil fuels, even as these are required to reduce substantially their GHG emissions.

The general lesson is that broad assumptions about the undesirability of fossil fuels need to be re-evaluated.

The general lesson is that broad assumptions about the undesirability of fossil fuels need to be re-evaluated. Fossil fuels are plentiful. We can use them with minimal environmental impacts if we want to. If we recognise that the end we seek is a clean and enduring energy system, not a particular form of energy or a particular amount of energy efficiency, fossil fuels may end up sustaining a much more important role in the energy system than many people – perhaps especially environmentalists – believe they would or should.

From a policy perspective, this means that our policies for clean energy should not be biased against or in favour of any particular form of energy, should not require a minimum production of renewable energy or nuclear power or a minimum amount of energy efficiency, or set a target for abolishing fossil fuels. Instead, our policies should focus explicitly on our specific environmental objectives. In the case of the climate change risk, this means that our policies should levy a fee for GHG emissions or set a regulated emissions cap that is enforced by penalties, and these should be set to attain levels of GHG emissions reduction consistent with the environmental imperatives that scientists are arguing for.

This does not mean that other policies are ruled out completely. In some cases, the inadequacy of market responses to price signals may require particular technology focused policies. But even such policies should be as flexible as possible while sticking to the specific environmental concern. An example is the California vehicle emissions standards. These do not mandate vehicle energy efficiency, although energy efficiency may be one way for manufacturers to achieve the emissions targets. These standards also do not require a particular form of energy (ethanol, electricity or hydrogen) or a particular technology (battery-electric car, plug-in hybrid, hydrogen fuel cell). They simply require that personal vehicles reduce their emissions and that vehicles whose emissions are

zero or almost zero must gain a growing share of the market, and manufacturers must meet these requirements collectively or face individual penalties.

If societies forgo the temptation to see the world in terms of good guys and bad guys, they will design policies that focus directly on their environmental objectives. If they do so, many people anxious about our unsustainable energy system will be surprised to discover that fossil fuels may very well be our friend rather than our foe.

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